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U. S. NAVY BATTLE DAMAGE PICTURES FROM WORLD WAR II.

BY COMMANDER ERNEST C. HOLTZWORTH, U. S. NAVY.

PART 4

The following collection of photographs, the fourth and last of the series, is devoted entirely to ships damaged by suicide plane (Kamikaze) attacks. All are official U. S. Navy photographs. A brief account of the circumstances involved in the damage each ship incurred is included as a matter of general interest.

Photo 1: Fighting fire on the flight deck of U.S.S. *Saratoga* (CV3) on 21 February, 1945. *Saratoga*, a unit of a task group, was engaged in maneuvers supporting amphibious operations at Iwo Jima when she became the target for a highly coordinated and well executed attack by Japanese suicide planes. During this attack four suicide planes (three of which carried bombs) crashed into *Saratoga* and one bomb hit the flight deck forward. Two hours later, a single Japanese plane scored a second hit with a bomb. Summarizing, *Saratoga* was damaged by four Kamikazes and five bomb detonations.

The photo shows the fires caused by two of the Kamikazes. One of these crashed forward on the port side of the flight deck and the other on the starboard side of the flight deck immediately forward of the island. The ensuing fires enveloped some of *Saratoga's* own planes parked in the areas. In one of the finest firefighting efforts of the war both fires were prevented from spreading, quickly brought under control and extinquished. Note the large-scale use of fog foam, which appears as snow in the photo.

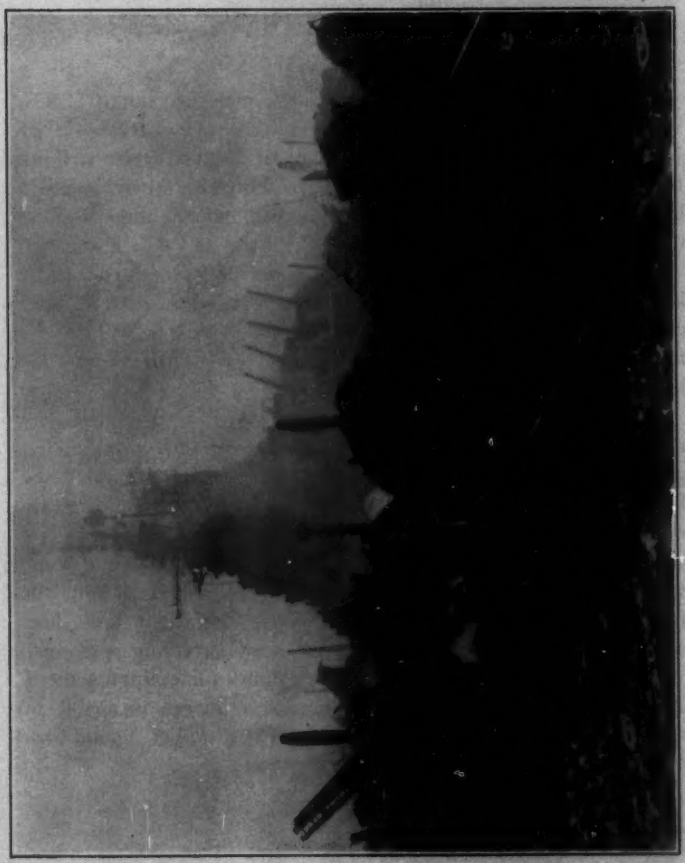
Saratoga suffered considerable damage from the other Kamikazes and bombs, including some underwater damage. She could not operate aircraft. Hence, she returned to Navy Yard, Puget Sound. for permanent repairs.

U. S. S. "SARATOGA" (CV3).

Photo 2: The aftermath of a flight deck fire on the U.S.S. *Bunker Hill* (CV17), 11 May 1945. On this date *Bunker Hill* was the flagship of a fast carrier task force operating off of Okinawa. Two Kamikazes, each with bombs, crashed the ship. The first of these crashed into the flight deck abaft the after elevator, releasing a bomb which penetrated the flight deck on the port side and passed through the skin of the ship at the gallery level detonating in air doing considerable fragment damage to the port shell. The plane skidded across the deck, setting on fire planes parked in the area, and then went overboard on the port side, leaving an intense fire in its wake. The second Kamikaze crashed into the flight deck at the base of the port side of the island. The bomb from this plane detonated in the gallery below, starting a bad fire in the gallery and hangar.

The photo shows remains of *Bunker Hill's* planes on the after portion of the flight deck. This fire was controlled in 1½ hours and extinguished shortly thereafter. The fire in the hangar was more difficult to control and was not extinguished until about two hours after extinguishment of the flight deck fire. The smoke seen aft of the island is coming from the hangar fire which was almost extinguished at the time the photo was made. *Bunker Hill's* effective damage control measures prevented a critical situation from developing despite serious damage and extensive fires. She never lost power and full firemain pressure was maintained at all times, despite bad smoke conditions in engineering spaces.

She returned to Navy Yard, Puget Sound, after brief stops at advanced bases.



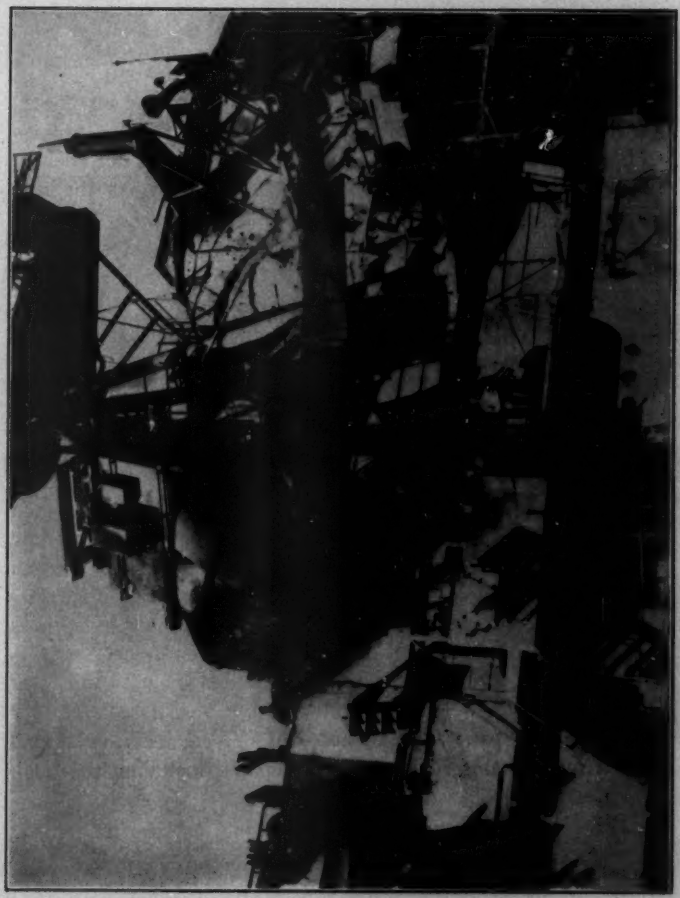
U. S. S. "BUNKER HILL" (CV17).

Photo 3: Damage to the forward five-inch director of U.S.S. *Ticonderoga* (CV14), caused by a suicide plane crash on 21 January 1945. *Ticonderoga* was a unit of a fast carrier striking force participating in operations off of Formosa when damaged by two Kamikazes. Each carried bombs, which added to the damage.

The first plane crashed into the flight deck forward of the island, its bomb detonating in the hangar below. An intense conflagration occurred among planes in the hangar. While this fire was being fought the second suicide plane crashed into the base of the forward five-inch director.

The photo shows the damage to the ¾ inch STS structure below the director. The top of the island was engulfed with flaming gasoline. The bomb carried by the plane detonated above the flight deck a few feet off of the port side of the island. Fragments caused widespread damage and started a flight deck fire among planes parked there. Casualties from this crash and bomb were heavy among personnel stationed in the island. Despite the numerous personnel casualties the island and flight deck fires were quickly controlled and extinguished by surviving personnel.

The hangar fire required about three hours for extinguishment. *Ticonderoga*, her flight deck and hangar rendered incapable of operating aircraft, returned to Navy Yard, Puget Sound, for repairs, after brief stops at advanced bases.



U. S. S. "TICONDEROGA" (CV14).

Photo 4: The point of impact of a suicide plane on U.S.S. *New Mexico* (BB40), 12 May, 1945. On that date *New Mexico* had been operating off Okinawa and was approaching her anchorage when attacked by two suicide planes. One struck the ship causing the damage shown—the other was shot down.

The plane which caused the damage approached from starboard and dived into the starboard side of the superstructure deck at the base of the smokepipe. The bomb carried by the plane detonated at the instant of the crash and caused widespread fragment damage. The usual gasoline fire occurred.

The photo presents a view of the damage looking down from a high platform. Note the large hole at the base of the smokepipe. Excess air pressure had been built up in the steaming firerooms (Nos. 1, 3 and 4) as the ship went into action. Possibly due to this, flarebacks of only minor proportions occurred in Nos. 1 and 3 firerooms. Nos. 1, 2 and 3 boilers were flooded partially by firefighting water draining down the uptakes. Some tubes in Nos. 1 and 3 boilers were cut by fragments from exploding small caliber ammunition which had been carried into the uptakes by the impact of the plane. Most serious boiler damage was to the brickwork—the fireboxes having been flooded with saltwater while still hot.

After minor repairs at an advanced base, *New Mexico* returned to the United States for permanent repairs, including thorough boiler overhaul.

U. S. S. "NEW MEXICO" (BB40).

Photo 5: Damage caused by a suicide plane to the U.S.S. *Isherwood* (DD520) on 22 April 1945. On that date *Isherwood*, operating off of Okinawa, was struck by a suicide plane which crashed into the starboard side of 5 inch mount No. 3. The bomb carried by the plane detonated with the impact and completely destroyed the mount, the foundation of which is shown in the photo.

The usual gasoline fire occurred and engulfed a port depth charge stowage. One of the charges exploded, possibly with a low order detonation, blowing the hole shown in the photo in the port stringer strake (of ½ inch STS). Fragments, either from the bomb or depth charge, passed down and riddled a shell strake below the waterline in the after engine room. The after engine room quickly flooded.

After temporary repairs at an advanced base *Isherwood* returned to Navy Yard, Mare Island, for permanent repairs, making the passage on the forward engine room.

U. S. S. "ISHERWOOD" (DD520).

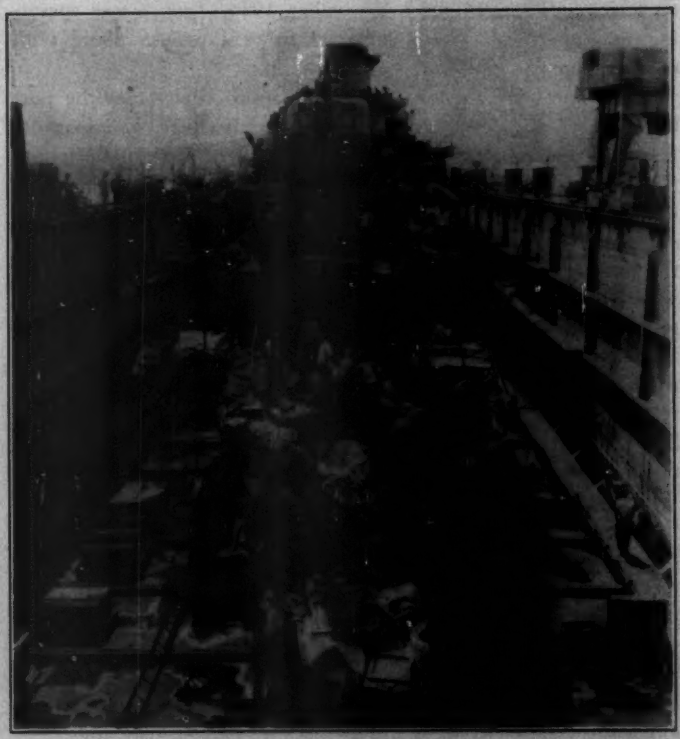
Photo 6: The U.S.S. *Sigsbee* (DD502) in drydock at an advanced base in April, 1945. She was struck by a suicide plane on 14 April 1945 while operating off of Okinawa.

The Kamikaze, with bomb load, crashed into the main deck abaft the aftermost 5 inch mount. The bomb load (possibly two bombs) detonated with the impact blowing off the upper portion of the stern as shown in the photo.

Note the remains of the steering gear. The rudder was intact but badly warped and wrinkled. The after section of the port shaft, with propeller and after strut, was missing. Oddly enough, the starboard shaft remained intact and was operable. Although towed to a floating drydock at an advanced base where the photo was taken, *Sigsbee* assisted with her starboard propeller.

While afloat she was well down by the stern, with the main deck awash at the after quarter point. Effective damage control work prevented a serious stability and flooding condition from occurring. The usual gasoline fire was extinguished quickly as the stern settled.

Sigsbee was repaired at Pearl Harbor, making the journey from the forward areas under her own power with the starboard shaft.



U. S. S. "SIGSBEE" (DD502).

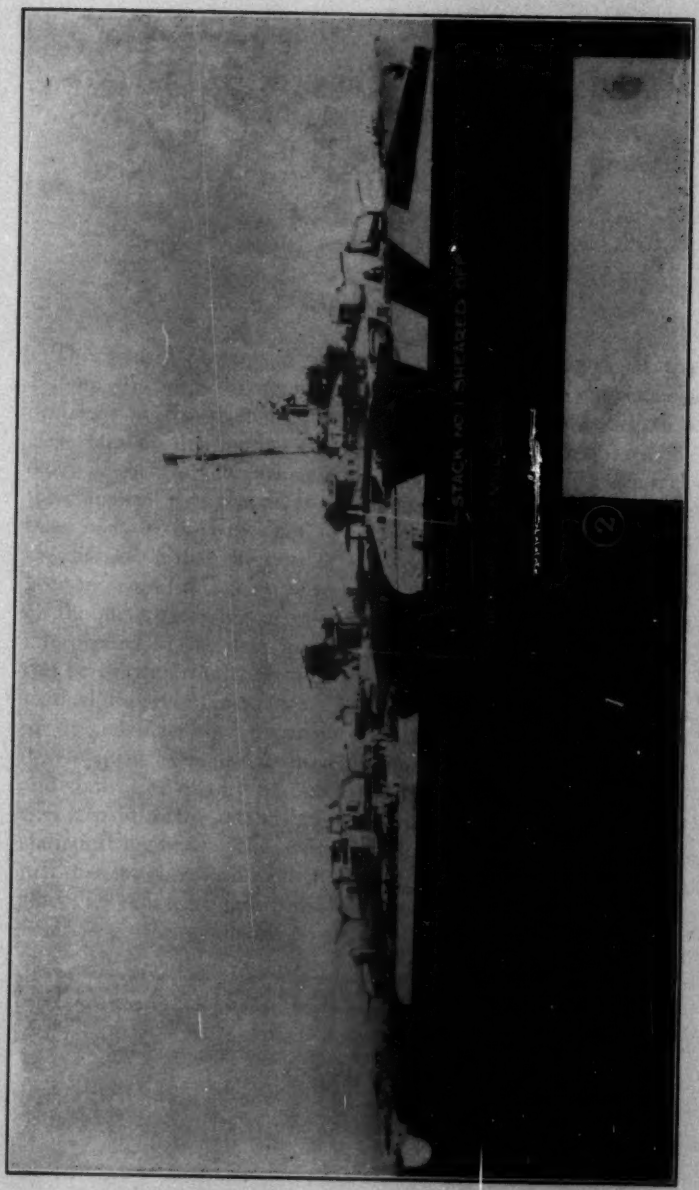
Photo 7: The U.S.S. *Ammen* (DD527) at an advanced base on 4 November, 1944. On 1 November, 1944, *Ammen* was operating in Leyte Gulf when damaged by a Japanese plane with obvious suicidal intent.

The plane, a twin-engined bomber, approached from the port bow, grazed the port side of the bridge structure, and was deflected in between the two stacks. As will be seen in the photo the forward smokepipe was completely severed and the after smokepipe nearly severed. The plane then went overboard on the starboard side. The usual gasoline fire was of minor proportions, the bulk of the gasoline from the plane's tanks going overboard with the plane. Alert damage control personnel quickly extinguished the small fire.

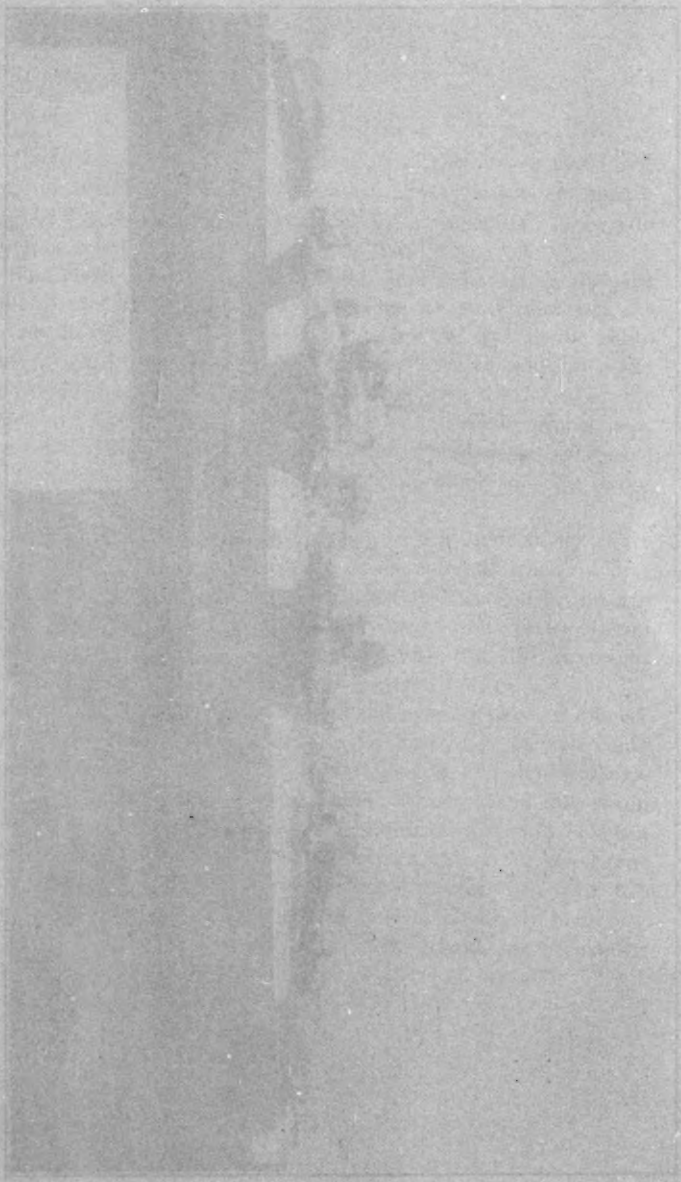
Personnel in the machinery spaces were not immediately aware of the crash. Their first intimation of damage was when the firerooms filled with smoke. Exhaust gases were sucked in through boiler air intakes, which, although intact, were warped and cracked on the port side permitting leaks into the firerooms (*Ammen*, of the 2100 ton class, has open firerooms).

By blanking off boiler air intakes and opening doors to blower rooms and main deck hatches to the firerooms *Ammen* could make steam for 32 knots for a brief period, although temperatures in both firerooms were excessive. It was found that steam for 27 knots could be made without too much discomfort. When making this speed the lower portion of the after smokepipe casing was cooled by fog spray using twelve foot (12 ft.) applicators. Otherwise the casing became dangerously hot.

Ammen returned to Navy Yard, Mare Island, for permanent repairs.



U. S. S. "Aaron" (DD527).



STATISTICAL INFERENCE APPLIED TO NAVAL ENGINEERING.*

By J. H. Curtiss, Lt. Commander, U.S.N.R.

Abstract.

This article presents a general account of the work of the Bureau of Ships in applying analytical statistical methods to problems in Naval engineering. An attempt is made to give a clear idea of the specific contribution of the statistical methodology in each of the various applications described. To this end, the statistical background is discussed at some length, both in the main body of the paper and in an Appendix. It is brought out in the discussion that the type of statistical methodology which has been most useful is the type in which the emphasis is not so much on the mere gathering of relevant data, as on the processing and interpreting of the data in such a way that probable inferences can be drawn from them through the use of the modern mathematical theory of statistics. The applications comprise studies of the engineering performance of the fleet, research in and development of materials used in shipbuilding and maintenance, and control of quality of purchased materials. Particular attention is paid to the establishing and enforcement of standards by statistical methods. The article concludes with emphasis on the fact that the statistical methodology is only a tool of the engineer, albeit at times an indispensable one, and is no substitute for sound engineering theory.

* The material in this paper formed the substance of two lectures delivered on 5 December 1945 by Lt. Commander Curtiss to the personnel of the Department of Naval Architecture and Marine Engineering of the Massachusetts Institute of Technology.

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1. Introduction

An interesting current development in the science of engineering is the increased use of the methods of modern statistical analysis in dealing with problems of variability. The Bureau of Ships of the Navy Department has been actively interested in this development for some time, and during the last three years has maintained a unit devoted entirely to engineering statistical analysis. The work of the unit has covered a broad field, which has included studies in operational analysis and the application of statistical inference to many types of industrial research and quality control problems. Until now there has been available no comprehensive summary of the work as a whole, although a number of requests have been received for such a report. It is believed that such a summary might be useful not only to Naval engineers as indicative of the value of these new techniques for their profession, but also to engineers and statisticians in general as suggestive of the versatile rôle which statistical methods can be expected to play in engineering science in the future.

Accordingly, the present paper will give a general account of the work of the Bureau of Ships in the field of engineering statiscal analysis. It will be realized that the rendering of a complete bill of particulars would be impracticable. Consideration of security and of commercial confidence are involved; and also, there is a good deal of duplication of methods and purpose among the very many individual projects which have been undertaken. Thus an attempt will be made to give the reader a fairly clear idea, not of the quantity of work which has been done, but rather of the specific contribution of statistical analysis in the various areas which have been cultivated.

The exposition will be nontechnical, and familiarity with modern statistical terminology and methodology will not be assumed. It has therefore seemed appropriate to take pains to place the description of the actual work itself within its proper context of statistical theory and philosophy, to the end that in each case the specific contribution of statistical methodology will be clarified, and also to the end that the reader will more readily perceive the generality of these particular applications of statistical methods.

A word of explanation to the professional statistician is in order. It has become fashionable lately, when expositions of this type are written or commented upon by responsible mathematical statisticians, for the writer or commentator to dwell at great length on the perils of indiscriminate application of the newer statistical methods. The tendency of responsible promoters of engineering statistics to issue warnings of this kind is quite understandable, especially in the light of the current scarcity of competent theorists. However, the central purpose of this paper is to describe a mathematical model in a readable manner, and then to produce a parade of more or less successful engineering applications of this model. The paper is not intended to be useful as a manual or textbook which will enable the reader with no previous statistical background to make immediate application of the techniques under discussion. It has therefore been considered appropriate for the most part to omit elaborate admonitions about possible discrepancies in practice between the model and the physical applications. The engineer will know from his own experience that there is often a wide gap between mathematical theory and the engineering realities. He will realize, to adopt a metaphor, that this article merely describes a new medicine, telling what it did in certain cases, and that a competent doctor will usually be needed to prescribe it.

2. Historical Sketch.

For some time it has been recognized by many thoughtful engineers that the classical engineering training has been weak on the subject of variability. In fact, it has occurred to some that the usual theory taught in engineering courses could even be called deficient from a quite practical point of view, because it makes no systematic provision for the variations from the theory which will surely be observed in practice. A curve in an engineering text is never a curve in the laboratory or in the shop; rather, it is a *band*, and the probable width of this band is often of as great practical importance as the position of the center.

At the same time that realization was growing among some engineers of the need for effective methods for dealing with variability, the more urgent demands of scientists in other fields in which statistical methods had always been heavily used were

causing a remarkable, in fact almost revolutionary, development of statistical technology to take place. During the last twenty years, through the contributions of a number of able mathematicians, physicists, biometricians, engineers, and inventors, the depth and power of the science of statistical analysis has been greatly increased. The theory of statistics has been identified as a department of the mathematical theory of probabilities; and important additions have accordingly been made to the already substantial literature of this branch of mathematics. Methods of collecting and classifying data have been greatly improved. The making of summaries and of more complicated calculations has been much facilitated by the invention of various types of electric calculating machines. Most important of all, the relationship between theory and observational data has been carefully explored and clarified.

Numerous apparently intractible problems of variation in biology and in the social sciences were first successfully attacked by the new statistical methods, which were thereupon given considerable publicity by students in such fields. It was inevitable that in spite of a rather formidable barrier of terminology and notation, the newly enriched statistical technology would sooner or later come to the attention of engineers in their dealings with the problems of variability. Dr. W. A. Shewhart and his associates at the Bell Telephone Laboratories seem to have been the first in the country to develop and publicize the application of statistical analysis to the technical problems of the engineer. The initial publication, a pamphlet written by Dr. W. A. Shewhart and entitled "Quality Control Charts" (ref. (a)), was published in November, 1926. Five years later, Dr. Shewhart's important and well-known treatise on "Economic Control of Quality of Manufactured Product" (ref. (b)), appeared. At about the same time, two of Dr. Shewhart's colleagues, Mr. H. F. Dodge and Mr. H. G. Romig, opened the field of statistically based sampling inspection (ref. (c)).

Appreciation of the utility of the new methods on the part of engineers and management grew slowly at first. For a number of years Dr. Shewhart and his disciples carried on an active "selling" campaign, which was greatly augmented during the late war by the instructional courses given all over the country by the

Quality Control Program of the Office of Production, Research and Development of the War Production Board, under the leadership of Dr. Holbrook Working. The situation at present in private industry is that certain of the simpler statistical techniques advocated by the Shewhart school (notably the "control chart" technique) are now generally recognized as indispensable tools of engineering science and management. Practically all larger corporations and many smaller ones now have units devoted more or less completely to statistical quality control work. As of January 1, 1945, there were some 30 separate regional organizations with a primary interest in engineering statistics and statistical quality control. These are now being welded into a national body, called the Society for Quality Control, founded under the original sponsorship of a subcommittee of the National Research Council.

While industrial interest in statistical methods has to date been centered upon the control of production processes which have passed the experimental stage, nevertheless appreciation is rapidly developing in industry of the utility of modern statistical methods in the design of laboratory tests and the analysis of production data for purposes of development of materials and processes. In addition, the newer statistical methods have been successfully applied to certain types of problems connected with plant maintenance and efficiency. Quality control of manufactured products, research and development, the proper operational maintenance of engineering plants—all these engineering problems are of vital interest to the Navy. The applications of statistical inference to be described in the later sections of this paper will cover a broad field of engineering activities of this nature.

3. Statistical Background.

An extended technical exposition of the principles of statistical inference would be out of place here. It is believed, however, that for readers entirely unfamiliar with the newer statistical methodology, the significance of its role in the applications described in the sequel could be clarified by presenting some of the fundamental concepts in a very general and nontechnical manner. The present section will be devoted to such an exposition. It will be supplemented by an Appendix, in which a more detailed, but

still nonmathematical, development will be given for readers who may wish to go somewhat more deeply into the matter without plunging into the rather forbidding and confusing literature of the subject.

It is generally recognized that by statistical methods is meant the science of *gathering* and of *interpreting* data. The technical problems involved in merely the *gathering* of data should not be minimized, but the major problems in statistical methodology center about the *interpreting* of data and drawing therefrom the right conclusions. When an investigation calls for a complete enumeration or detailed survey of a population, as in the case of certain inventory and census projects, the interpretation of the data usually can be accomplished by convenient simple condensations and pictorial representations.* The recent great extension in the power and applicability of statistical methods, which was previously noted in Section 2, has consisted chiefly in the development of improved methods of interpretation in the more difficult case of statistical investigations in which the data gathered constitute only a portion, or *sample*, of the totality of relevant observations which could be made. In such cases, the central problem of interpretation is to draw from the sample an *inference* about the totality or *population* of potential observations.

The theory of interpreting sample data for inferential purposes now forms the main body of modern statistical theory, and as before stated, is a branch of the mathematical theory of probabilities. The inferential type of statistical methodology has become synonymous with *analytical* statistics in the thinking of many professional statisticians. Practically all the applications of statistical methodology to be considered in this paper involve statistical inference.

When the methods of statistical inference are to be applied to a sample of observations on a given engineering variable (such as the tensile strength of brass rod or the hourly underway fuel consumption of a Naval vessel), the first step is to separate the variation which occurs in the observations into two components. One of the components consists of the systematic variation due to known and assignable causes (that is, causes such as the nominal

* It is worth noting here that the recent improvements in the theory of sampling have brought about a greatly increased use of sampling censuses and inventories where previously 100 per cent methods were used.

thickness, the composition, and the temper of the tested specimens of brass rod).* The other component of variation consists of a residual which is ascribed to chance.

If in any given case the assignable causes are all subjected to a completely definite specification (in the sense that each of the subsidiary variables representing these causes is assigned a specific numerical value), then all the variation in the observations must belong entirely to the chance component. When a variable has been so restricted that variations will be ascribed entirely to chance, the variable is called a *statistical variable* (or *variate*, or *random variable*, or *stochastic variable*). The theory of statistical inference is essentially the theory of statistical variables. The separation of the variability of an engineering variable into systematic and chance components reduces the study of this variable to that of one or more statistical variables.

To draw useful inferences from a sample of observations on a statistical variable, it is necessary to make certain assumptions as to the character and permanence of the pattern of variation exhibited by the variable. More specifically, it must be assumed that all possible sequences of observations on the statistical variable are produced by a stable complex of causes which makes the individual observations take on the various different possible values of the variable with fixed probabilities. These probabilities are idealized relative frequencies which would be approximately and uniquely determinable if the number of observations in any sequence were increased sufficiently. When the sample is taken from a finite but unknown population, as in lot acceptance sampling inspection, the method of drawing sample observations is usually such that the probability of an observation falling in a given range of values is equal to the relative frequency of such values in the population; this result is achieved by what is known as "random" sampling. When the sample is more properly thought of as being drawn from an infinite hypothetical population, as is usually the case in laboratory experimentation, then

* The decision as to which causes of variation are to be isolated and controlled in a given application is often based largely on economic or administrative considerations rather than on theoretical statistical considerations. For example, in the case of the hourly underway fuel rate of a steam-driven ship (see Section 5), it would be quite possible to isolate many causes of variation, such as speed, displacement, number of boilers in use, method of operation of plant, squat and trim, wind, seas, etc. But for logistics purposes it is at present economically feasible (and tactically necessary) only to treat speed and displacement as assignable causes, and to throw the remaining variability into the random component.

the practical interest in the inference is centered on the behavior of future samples rather than on the nature of the hypothetical population. Here the sampling probabilities are not directly supported by tangible (though unknown) relative frequencies in the population.

The different possible values of the statistical variable assumed by repeated observations on it, together with the respective probabilities of occurrence associated with these different values, are collectively called the theoretical frequency distribution (or probability distribution) of the statistical variable. An example of such a theoretical frequency distribution is given graphically in Figure 1, which is discussed in further detail in the Appendix.

In the study of statistical variables, the standard approach is to make certain reasonable *a priori* assumptions about the general form of the theoretical distribution, leaving as unspecified the values of various determining constants of the distribution. These so-called *population parameters* are then estimated, or various hypotheses concerning them are tested, by means of calculations involving the actually observed values in the sample of observations.

Thus in a typical case, it might be assumed from certain physical considerations that the theoretical frequency distribution of a statistical variable, such as the tensile strength of brass rods of a preassigned nominal size, composition, and temper, is defined by areas (see Figure 1) under a curve whose equation is of the form

$$z = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(x-\mu)^2}{2\sigma^2}} \tag{1}$$

in which the values of the constants μ and σ are initially undetermined. Then when a sample of observations becomes available, appropriate functions of the data are used to estimate μ and σ, or to test hypotheses concerning their general location such as the hypothesis that the arithmetic mean μ is any number less than, say, 60,000 p.s.i. The actual details of how such estimates and tests are set up will not be presented here, but an example is given in the Appendix.

It should be mentioned in passing that μ is the centroid of the particular distribution defined by (1). The centroid is called the arithmetic mean, or more simply, the *mean* in statistical work.

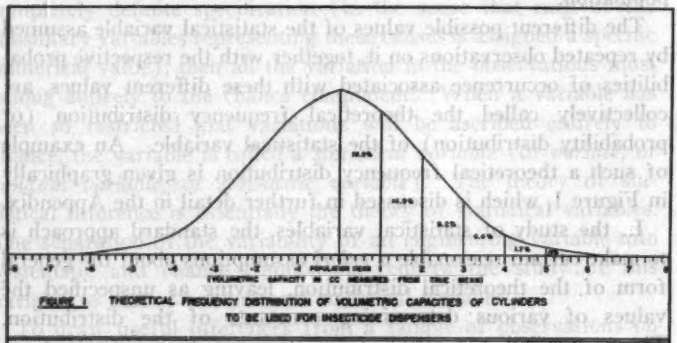

FIGURE 1 THEORETICAL FREQUENCY DISTRIBUTION OF VOLUMETRIC CAPACITIES OF CYLINDERS TO BE USED FOR INSECTICIDE DISPENSERS

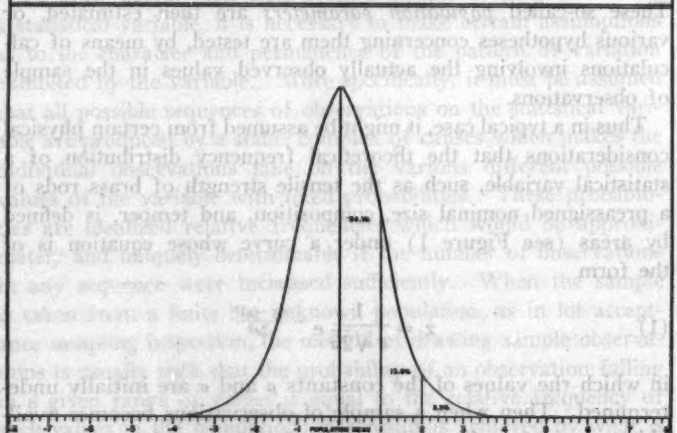

FIGURE 2. PROBABILITY DISTRIBUTION OF MEAN OF RANDOM SAMPLE OF 4 CYLINDERS (CALCULATED FROM THEORETICAL DISTRIBUTION IN FIGURE 1)

Furthermore, σ is the square root of the second moment about the centroid, which is called the *standard deviation* in statistical work. The mean and standard deviation of any distribution respectively define the position and measure the dispersion of the distribution. Since for many purposes, the position and dispersion are the two most important characteristics of a distribution, the mean and standard deviation have come to be the classical tools of the statistician in describing distributions.

A most important intermediate step in both the problem of estimation and that of testing hypotheses consists in determining the probability distribution of the particular functions of the sample data (such as the arithmetic mean of the sample) which will be used to do the estimating or testing. Figure 2 illustrates the probability distribution of the arithmetic mean of a random sample of four observations drawn from the population illustrated in Figure 1, and Figure 3 illustrates how this calculated probability distribution is used in testing a statistical hypothesis. Both figures are to be discussed in considerably more detail in the Appendix. A great deal of the literature of modern mathematical statistics is concerned with such distribution problems, and with the related search for the "best" estimating functions and tests.

When a statistical hypothesis has been set up, such as the hypothesis mentioned above that the unknown mean of a given theoretical frequency distribution of tensile strengths is less than 60,000 p.s.i., there are available in general infinitely many tests of this hypothesis based on sample data, corresponding to various ways of handling the sample data and of choosing the sample size (that is, the number of observations in the sample). In the case of any one test, it is always possible theoretically to arrange matters so that if the hypothesis is true, then there is a fixed, preassigned probability (say 0.05) of erroneously rejecting the hypothesis because of a sampling accident. (This probability is called the *significance level* of the test. In the test illustrated in Figure 3, the significance level of the test is 0.023 for the hypothesis denoted by H_0 in that Figure*.) The deciding factor in choosing which test to use is that if the hypothesis to be tested is not true, different tests with the same significance level have

* See Appendix, paragraph 11.

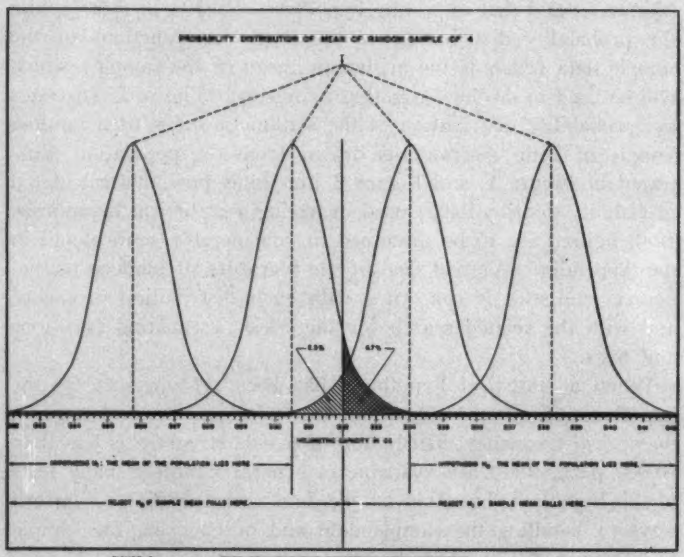
PROBABILITY DISTRIBUTION OF MEAN OF RANDOM SAMPLE OF 4
2.5%
2.5%
HOLDING CAPACITY IN cc
REJECT H_0 IF SAMPLE MEAN FALLS HERE
REJECT H_0 IF SAMPLE MEAN FALLS HERE

FIGURE 3 TEST OF HYPOTHESIS CONCERNING POPULATION MEAN
(ASSUMPTIONS: NORMAL DISTRIBUTION OF POPULATION WITH VARIANCE = 4.)

different probabilities of indicating this fact. In other words, different tests have different abilities to discriminate between sets of alternate hypotheses, and the proper test to use is the one which has the appropriate discriminating power or accuracy. The discriminating power of a test can be quantitatively characterized in terms of probabilities, and in most cases these probabilities can be calculated or estimated in some way *before* any sample data are obtained. Once the necessary discriminating power has been decided upon, it is usually a simple and routine matter for the professional statistician to pick out the right test to do the job.

This discussion brings out the fact that in any investigation in which a decision is to be based on a test of a statistical hypothesis, it is an essential preliminary step to decide very definitely on just how much discriminating power is really needed. This involves a balancing of economic and engineering considerations, since higher discriminating power (assuming that the sample data are used as efficiently as possible*) usually means more observations in the sample, and therefore more expense.

The planning of a statistically based investigation so that it will have the desired accuracy is one phase of the statistical technique known as the design of experiments. This technique may be generally defined to consist of the planning of sampling investigations and laboratory experiments involving variable material with a view to defining the main problems in terms of statistical hypotheses in such a way that conclusions can be reached with the least effort and expense, consistent with the accuracy desired.

The technique of experimental design is particularly valuable in case the aim of an investigation is to compare a number of different materials, treatments, processes, etc. From a statistical point of view, such an investigation usually involves the testing of hypotheses concerning differences between various population parameters; in particular, differences between means and standard deviations. By means of a generalization of the

* This assumption is not always fulfilled when tests of statistical hypotheses are devised by amateurs on intuitive grounds. For example, a specification used throughout the war for a certain type of plastic armor required that the mean of the three largest observations in a sample of five observations be used in an acceptance test which was essentially a test of a statistical hypothesis. The use of such a function of the data amounts to throwing away a considerable portion of the information in the sample, and provides much less discriminating power than the maximum power available with a sample of 5.

type of theoretical frequency distribution which would be assigned to a single statistical variable, and which is discussed in the Appendix, paragraphs 17 to 26 inclusive, it is possible to set up a mathematical model for experimentation in which a number of possible assignable causes of systematic variation are permitted to be present simultaneously, and their individual effects are then disentangled and appraised in the ensuing analysis. The essential feature of the model consists in expressing the engineering variable under study as the sum of a statistical variable and a systematic variable which is a mathematical function of the assignable causes. When an experiment has been properly designed so that this model is applicable, it is called a *factorially designed experiment.* The variation in the resulting observations is analyzed by a technique known as the *analysis of variance* to determine which of the assignable causes (or factors) affecting the variability are the significant ones and to estimate the magnitude of their effects. For a given discriminating power, a factorially designed experiment is often far more economical than a series of controlled experiments in which one assignable cause is investigated at a time by rigidly and artificially fixing the values of all other causal variables. Indeed, there are many cases in which completely controlled experiments are out of the question, and a factorially designed experiment is the only answer.

The broad essentials of the methods of statistical inference used in the applications to be described in the succeeding sections have now been sketched. To summarize, the primary operations are

(1) The *specification* (with supporting evidence) of a general law of probability, or probability distribution, which governs the variation in a statistical variable.

(2) The *estimation* of parameters of the general probability distribution specified in (1) by using appropriate functions of sample data.

(3) The *testing of hypotheses* concerning the parameters of one or more previously specified general distributions by using appropriate functions of sample data.

The liaison between these statistical operations and the applications is furnished by the doctrine of the design of experiments,

which is concerned with the formulation of the practical problem in terms of statistical hypotheses in such a way as to achieve the desired accuracy and to get the most information out of the least amount of data.

The procedure which has been outlined above is simply a particularization of what might be called the standard scientific method. In any systematically conducted scientific inquiry, a general theory for the experiment is first formulated; this step in the statistical case consists of specifying the underlying theoretical frequency distribution. Then an experiment is performed which yields data, and the data are used to fill in gaps in the original theory, or to test the correctness of the theory. In the statistical case these uses of the data consist respectively of the estimation of population parameters and the testing of hypotheses.

Another possible parallel is with the promotion of a business enterprise. Various probabilities are assessed roughly to start with, and then the data from the first period of operation are used to refine original estimates, test original assumptions, and furnish a basis for definitive forwarding planning.

4. Outline of Applications.

The applications of statistical analysis which will be discussed hereinafter may be conveniently fitted into the following outline.

I. Analysis of Engineering Performance of the Fleet.
   - A. Logistics studies.
   - B. Operational studies.
   - C. Studies of the performance of machinery and materials.

II. Materials Research and Development.
   - A. Comparison and improvement of materials and processes.
   - B. Development of engineering methods of test.

III. Process and Product Quality Control.
   - A. The establishing of standards.
   - B. The enforcement of standards.

5. Analysis of Engineering Performance of the Fleet.

A large amount of data on engineering operations of the fleet are patiently recorded and sent in to the Department by ships and

field activities. The very fact that there is so much of it imposes a serious barrier to the deduction of genuinely representative conclusions. On the other hand, in the case of many important topics, as will be brought out below, there are no reliable data available at all except possibly on board certain of the ships. Therefore in the studies of engineering performance of the Fleet the problem of gathering truly representative data is a serious one, and has sometimes outweighed the problem of interpreting it after it has been gathered. However, the methods of statistical inference have also played an important rôle, as will now be seen.

A. *Logistics studies.*

The most ambitious project under this heading has been one in which analytical methods have been used extensively. It has consisted of a study of the wartime fuel rates and cruising radii of all major surface combatant vessels. The usefulness of such information for design and logistics purposes needs no further comment.

The engineering basis for these fuel rate studies has been the relation between the hourly average propeller speed and the hourly fuel consumption of a ship underway. This relationship was chosen because of the existence of vast quantities of hour-by-hour observations on this pair of variables in the "Underway Data Sheets" (or "Daily Work Sheets"). From the point of view of statistical inference, the main problem was to estimate the regression coefficients and the dispersion in a simple regression problem* in which the fixed variate was the propeller speed. In accordance with the principles stated in the Appendix for attacking such problems, the raw data were subjected to a least squares curve-fitting process, here accomplished almost entirely by mechanized procedures, which provided simultaneous estimates of both the mean fuel rate and the dispersion about the mean (see Figure 4). From the resulting curves, estimates of endurances with tolerances were calculated by means of formulas derived by methods of mathematical statistics. To convert from time units to distance units, speed-Rpm. relations were obtained by empirical engineering methods, as statistical methods are at

* The statistical terminology and problem are explained in the Appendix, paragraphs 18-20 inclusive.

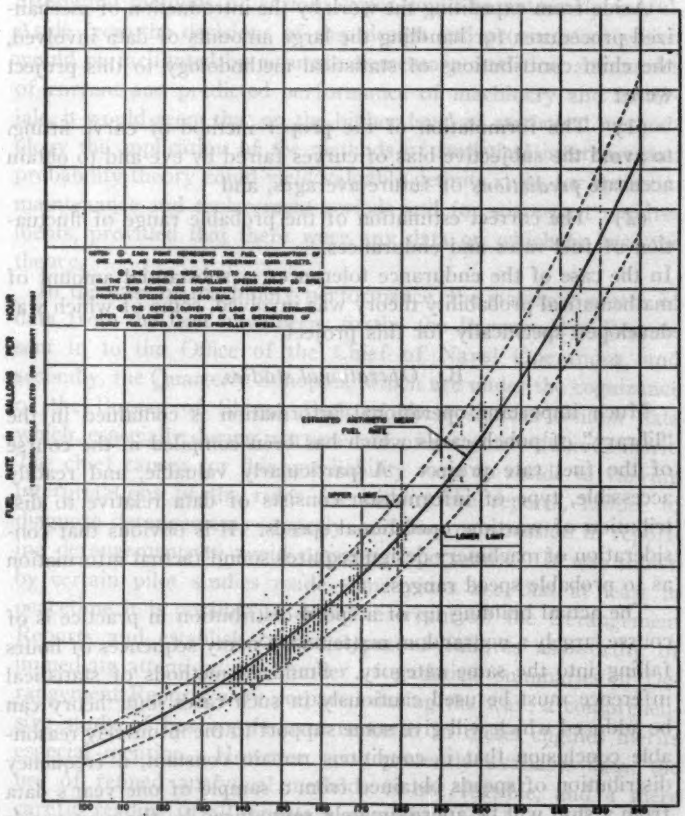

FIGURE 4. HOURLY FUEL CONSUMPTION OF A U.S. NAVAL VESSEL.

present not applicable to such calculations because of the lack of sufficient observational data. An idea of the scope of this project can be obtained from the fact that to date over 1,000,000 hours of steaming have been processed on individual punch cards.

Aside from expediting the work by the introduction of mechanized procedures for handling the large amounts of data involved, the chief contributions of statistical methodology to this project were:

(1) The formulation of the proper method of curve fitting, to avoid the subjective bias of curves faired by eye and to obtain accurate *predictions* of future averages, and

(2) The correct estimation of the probable range of fluctuation of fuel rates and endurances.

In the case of the endurance tolerances, a substantial amount of mathematical probability theory was involved, some of which was developed specifically for this project.

B. *Operational studies.*

Much important operational information is contained in the "library" of punch cards which has been compiled in the course of the fuel rate project. A particularly valuable, and readily accessible, type of information consists of data relative to distribution of wartime operational speeds. It is obvious that consideration of machinery design requires sound factual information as to probable speed ranges.

The actual building up of a speed distribution in practice is of course largely a nonrandom matter, with many sequences of hours falling into the same category. Standard methods of statistical inference must be used cautiously in such cases, but theory can be adduced which will give some support to the intuitively reasonable conclusion that if conditions remain constant, a frequency distribution of speeds obtained from a sample of one year's data from a ship will be approximately reproduced by the next year's data, and by another ship with similar duty.

C. *Studies of the performance of machinery and materials.*

In the case of these studies the chief difficulty has been one of obtaining reliable information. While on the whole, serviceability studies have not to date been as successful as some of the

other undertakings which are under discussion in this paper, it seems desirable to give space to these endeavors here because they deal with a subject which is of great importance. Moreover, this is a type of study in which given the right kind of data, inferential methods of various types could be extremely useful. Aside from the decisions of ship design and procurement which would be facilitated by accurate elementary statistical summaries of current and predicted performance of machinery and materials, it would seem that on the higher level of statistical methodology the application of the methods of statistical inference and probability theory could yield valuable definite rules for optimum maintenance and replacement periods and for spare-part requirements, provided that there were any data on which to base the theory.

In the case of machinery performance, the standard source of data from the fleet have been: firstly, the Derangement Reports sent in to the Office of the Chief of Naval Operations, and secondly, the Quarterly Synopses, which are under the cognizance of the Bureau of Ships. Both of these sources contain data which, especially during wartime, are of extremely dubious merit. The chief causes for this unreliability seem to reside in varying interpretations of the rules for making the reports, failure to diagnose derangements properly, and bias or omission in reporting derangements to avoid censure of personnel. It was shown by certain pilot studies made some years ago that at least in peacetime it is possible to skim the cream off the Derangement Reports and establish certain types of failures as worthy of immediate attention. A number of statistical summaries of Derangement Reports were prepared during the war; a comprehensive study of bearing failures reported in diesel engines merits especial mention. However, with presently available data, the use of refined analytical methods is not feasible, and a mere careful reading of all reports, such as was regularly done during the war, usually suffices to establish the main effects. In the attempt to open up new and more reliable sources of data, an ambitious program of microfilming the Machinery History Records of representative surface combatant ships is underway, and summaries and classification of the failures obtained in this way are currently being prepared.

In the field of service performance of materials, a particularly resolute attack has been made on the problem of appraising and predicting the service performance of various shipbottom paints. The difficulty here again has been lack of good data, the main trouble being that established methods of evaluating and reporting quality and performance of paint were too vague and subjective to be of much use for quantitative study. Analytical statistical methods have established an important negative result, however; namely, that estimation of the life of a paint system under war service conditions will never be possible within useful limits of accuracy unless certain key assignable causes connected with the application of a paint system are isolated, such as weather conditions, paint thickness, etc. The Docking Report Form was revised in 1944 with a view to providing more specific information, but the difficulty of securing accurate reports seems to persist.

An interesting example of what can really be done in the way of applying the methodology of statistical inference to a study of service performance of machinery when reasonably good data are available is furnished by the story of a recent investigation of piston ring wear on the main engines used for the CVE55 Class. These engines were Skinner "Uniflow" engines of larger design than had been built before, and numerous details of construction were necessarily extrapolated from the smaller designs. Serious piston ring wear was soon reported when the engines were put into service. About forty schools of thought, each with strongminded proponents, quickly developed concerning the matter. Oil experts, metallurgical experts, et.al., all had different ideas and were demanding different types of investigations. The Statistical Section of the Bureau of Ships was called in to assist a group of engineers in the Research Branch in their attack on their problem. The first step of the statisticians was to set up a carefully devised form on which data were to be recorded whenever an engine in one of several sample ships was to be pulled down. The form provided for a factorial analysis in which the five positions on each ring, the positions of the six rings on each piston, the five piston positions on each engine, the two engines on each ship, and the several sample ships, were all identified. The principles of design of experiment outlined in Section 3 above were thus put into effect. The result-

ing data, when subjected to the appropriate analysis of variance, indicated that the ship-to-ship variation in ring wear was the most important source of variability, that wear was fairly uniform for a given piston, and that there was a haphazard occurrence of ring-wear from piston-to-piston. These facts could not possibly be established from a cursory visual examination of the data; the statistical methods were really essential in sorting out the significant from the nonsignificant factors.

A supplementary analysis of the operating conditions of the sample ships revealed a not totally unexpected positive correlation between ship speed and ring wear. This suggested to the engineer in charge of the project in the Statistical Section that the increase in wear at higher speeds of operation was due at least partly to a greater dilution of oil by steam at the higher speeds, with a consequent decrease in the effectiveness of the lubrication of the cylinder. (It is to be noted here that the method of cylinder lubrication of these engines consists of injecting lubricating oil into the entering steam.) To verify this hypothesis, a sample of 17 CVE's was now selected for a statistical investigation into the correlation between concentration of lubricating oil and ring-wear under service conditions. Since the length of time that a given set of rings was in operation was obviously an important factor, the number of miles steamed by each ship at various speeds was also taken into consideration in this new study. The result of the investigation was that the diminishing oil concentration at higher speeds was found to be far more important in causing ring wear than the distance steamed before overhaul. The hypothesis of the engineer was now justified, and entirely new rules for lubrication rates for the engines were formulated, in which the recommended rate of lubrication was adjusted on the basis of the volume of steam flowing through the cylinders (which is roughly proportional to the cube of the shaft speed) rather than on the former basis of the area of the wiped surfaces (which is directly proportional to the shaft speed). At this writing, the ring wear problem seems to have been completely solved.

6. Materials Research and Development.

As indicated in the outline in Section 4, it is convenient for present purposes to divide the projects under this heading into

two main categories. The projects of the first category are those in which materials or processes are evaluated and compared by standard methods of test; while in projects of the second category, the interest is centered on the engineering details of the tests themselves.

Before proceeding to particulars, a few general remarks on the value of inferential methods in this field are in order. A great number of research projects were set up by the Armed Services during wartime, and present indications are that this sort of activity will be continued on a broad scale in peacetime. An appreciable proportion of those research projects have yielded quite unnecessarily inconclusive results, due to poor prior definition of the problem and the lack of a proper plan of experimentation. It is possible to make out a fairly strong case for the assertion that a number of these unsuccessful projects would have either been abandoned at the outset, or made to serve their purpose properly, if modern statistical principles of experimental design had been used in setting them up. For example, in nearly all of the completed research projects which yielded inconclusive results and which have come to the attention of the author, the simple question of how many repetitions to make had been answered entirely by guesswork, whereas the principles of experimental design could have provided a rational answer. It is also worth noting in this connection that one of the more important contributions of the statistical doctrine of experimental design to a research program lies in the fact that before it can be employed in setting up an experiment, *the engineering aims of the experiment must be clearly defined.*

A. *Comparison and improvement of materials and processes.*

In research in materials and processes by established methods of test, it has been found that the problem of formulating the appropriate experimental design and statistical tests assumes two rather different forms, which correspond respectively to the earlier and later stages of a research program. In the first form of the problem, the chief emphasis is on the design and analysis of complex factorial experiments, to the end that the advantages of the multiple regression model* will be fully utilized. Such

* See Appendix, paragraphs 18-26.

experiments, and their associated tests of hypotheses, are not intended to be ultimately conclusive, but merely serve to single out the principal assignable causes of variation and thus to set up guide posts which point the way of further more definitive experiments. An example of this type of experiment has already been given in connection with the piston ring wear problem in the preceding section, and other examples will be given presently. Since the chief error to be guarded against in this sort of experiment is an erroneous decision that a significantly large effect exists when in fact there is no such effect (an error which might lead to fruitless further experimentation) and since (as stated in Section 3) any properly performed statistical test will insure against this error regardless of the discriminating power of the test, the estimation of power in such cases is usually relegated to a position of secondary interest.

The second form of the problem, corresponding to the more advanced states of a research program, consists in setting up designs and performing resultant analyses for laboratory experiments or field tests of rather simple construction in which the purpose is to establish finally and conclusively which of two or more treatments, materials, etc., is the better. The essential point in setting up such a test is to attain the desired discriminating power. In most cases, this is largely governed by the sample size (i.e., the number of observations).

Since the examples of simple tests in which the main problem of experimental design was to calculate the required discriminating power are all rather similar from the statistical point of view, and rather less interesting than the more complex factorial experiments, there will be no attempt to go into the details of any one of them here. Successful laboratory tests of this class which were set up during the war in accordance with prestated power requirements include ballistic tests for the comparison of different types of metallic and nonmetallic armor, simulated service tests of life preservers (discussed in further detail below), and comparison tests for the shear strength of different types of plywood. It is also worth noting that statistically based lot acceptance sampling plans, which have been installed in many Navy Department purchase specifications, constitute in effect planned experiments in which the number of sample items is

calculated from the required power of discrimination between "good" and "bad" lots. More about this point will be found in Section 7.

Turning to the more complex aspects of experimental design as applied to research in materials and processes, the first example to be considered will be the in-service testing of various types of paint. It has been remarked in the preceding section that the appraisal of the performance of shipbottom paints from routine service reports is complicated by lack of control over the source of data. The most hopeful solution seems to lie either in the direction of panel tests or in the selection of a few vessels for experiments in which the condition of application and maintenance are reasonably all controlled. Accordingly, a number of panel exposure tests of paint have been laid out in replicated randomized block arrangements, and a factorially designed service test of paint above the waterline is currently underway on small vessels which return to port after short waterborne periods. The latter experiment is being performed on several sample vessels by a Navy Yard on each coast. The layout for each individual ship consists of 2 test blocks, one at the bow and one at the stern. Inside each of these two blocks, 9 different paint systems are applied to 9 fixed test patches in the block. In each block, the assignment of paint system to the possible positions in the test patch is made at random. Such a design will provide for efficient segregation of the following main sources of variation: different paint systems, different position of blocks on the hull, and different hull positions inside blocks. Older methods of systematically laying out tests of paint systems would demonstrably require more ships and fewer paint systems to achieve results of comparable accuracy and comprehensiveness.

To take a quite different example, in developing a specification for a pneumatic vest-type life preserver it was desired to determine the effect, if any, of immersion in gasoline for a number of hours on the buoyancy and on the seam strength of the life preservers of various different manufacturers. Some idea of expected variation was available from previous tests of a pneumatic life belt, so data were available on which to calculate the number of specimens to be tested to achieve the required discriminating power. The experiment was set up with 16 preservers from each

of 3 manufacturers. Eight from each group of 16 were tested after being subjected to gasoline immersion, and eight were tested without prior immersion. In addition, eight different positions were identified on each preserver to test the seams. In this way, a simultaneous comparison of treatments, of manufacturers, and of seam positions was obtainable from a single experiment, and the effect of any one variable was determined with approximately the same accuracy as would have been obtained if the entire experiment had been set up for investigating that variable alone. Significant differences were found in the mean values of several of the variables and various provisions were made for this in the final purchase specification for the life preserver. The estimate of the residual variation, obtained in the case of seam strength measurements from 384 observations on this variable, was proved by later experience in production to be entirely reliable.

In the development of metallurgical alloys, there are many opportunities for the use of factorially designed experiments to indicate possible directions in which to try changing the chemical composition and mill practice so as to improve the physical properties. One example is especially worth mentioning because it will serve to illustrate the point that factorial designs cannot be altered indiscriminately, once they have been properly set up. An extensive factorially designed experiment was authorized at one of the Naval laboratories to compare the effect of variations in carbon, manganese, and titanium in high tensile titanium steel plate, and carbon, manganese, and vanadium in high tensile vanadium steel plate. Three levels of each chemical were to be used, thus necessitating 54 heats. The other chemical elements were to be held constant throughout the experiment. Unfortunately, the laboratory personnel apparently became so intrigued with the idea of varying everything in sight all in one experiment, that they also varied another chemical element from heat to heat in a way unrelated to the underlying theory of experimental design. The result was a more or less serious confounding of effects, and while a considerable amount of the information originally sought can probably be salvaged from the data, the discriminating power of the original design was definitely impaired.

In a somewhat different line of research an especially interest-

ing application of experimental design has been made to the problem of evaluating camouflage measures. The basic variables to use in evaluating such measures are often clearly defined by the intended purposes of the measure; for example, in many studies the appropriate criterion is the difference between the true bow angle and the bow angle estimated by the observer, who is more or less confused by the camouflage. Different observers will react differently to the same camouflage measures, and the same observer may not react similarly to the same pattern twice. Since it may make a great deal of difference, in terms of lives and money, whether one camouflage measure is on the average just a little better than another, the usefulness of proper experimental design and statistical analysis is fairly apparent. Several fairly ambitious projects making use of factorial designs and dealing with both laboratory tests and field trials have been completed. Sources of variation which are present and must necessarily be studied in such projects are lighting conditions, range, ship type, and of course, the true bow angle. Unfortunately, considerations of security prevent giving further details here.

B. *Development of engineering methods of test.*

In the study of engineering methods of test, the problem so far attacked have fallen into several classes, which will be respectively discussed under the subheadings displayed below.

(1) *Studies of the precision of tests.*

The chief difficulty in the absolute determination of the precision, or reproducibility, of a test, particularly if it is of a destructive nature, of course lies in the fact that the variance due to testing error is usually hopelessly tangled up with the variance due to lack of complete uniformity of the tested material. Both of these sources of variability contribute to the random component as well as to the systematic component of variation of the test result. However, comparisons of the relative precision of two or more different types of test are often possible and useful. From a statistical point of view, such a comparsion ordinarily involves a simple significance test for the difference of two standard deviations, or for the homogeneity of a number of standard deviations. In setting up the corresponding experi-

ment, the usual questions of discriminating power must be considered.

A fertile field for this type of investigation has been the study of various types of tests for rubber products. Extensive "round-robin tests" are now underway, in which parallel samples submitted by various participating industries are being tested in various Government and commercial laboratories with a view to comparing the precision of various standard and new methods of testing for such physical properties as tensile strength before and after aging or immersion in some deleterious liquid.

(2) *Investigations of correlation between tests.*

Another common application of statistical analysis in the development of tests is to the study of the correlation between various related already-established tests, with a view to reducing the number of these tests to an essential minimum and to substituting simpler and less expensive tests for difficult and expensive ones. A good example of this type of study is the work which has been done on the problem of the relationship between the tensile and yield strength and measures of the hardness of metals. The interest in this relationship lies in the well-known fact that a hardness test is rapid and nondestructive and a tension test is relatively slower and more expensive. One of the first investigations into this subject made by the Navy Department during the war was a study of the relationship between Brinell hardness and tensile strength and yield point of high tensile steel, undertaken at the request of one of the shipbuilding yards. This project is described in vol. 57 of this Journal, from which Figure 5 was reproduced. The bands in this figure indicate the estimated limits for each value of Brinell hardness within which the tensile strength and yield point, if they were to be determined, would fall with a preassigned probability. The widths of these bands are just as important as the positions of their centers, for the problem here is not one of long-term averages, but one of judging each individual plate.

Another example particularly worth mentioning, although it is still in an embryo stage from a statistical point of view, is furnished by the new specification for naval wrought brass. The old Navy Department specification for this material, which had

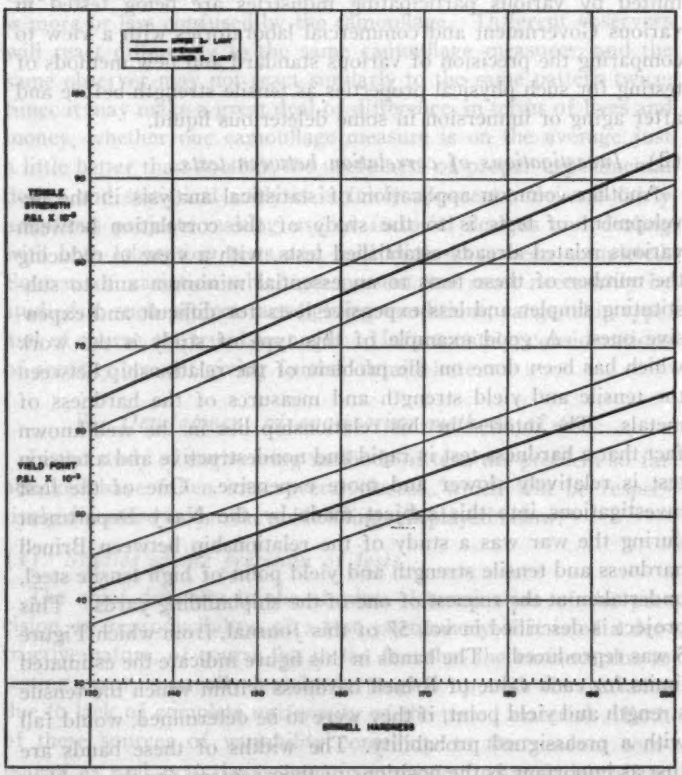

FIGURE 5. THE RELATION BETWEEN BRINELL HARDNESS, YIELD POINT AND TENSILE STRENGTH OF HIGH TENSILE STEEL.

remained essentially unchanged for many years, was recently given a thorough and much needed overhauling. One of the most interesting departures in the revision consists in a lot acceptance test in which determinations of Rockwell hardness on a number of specimens from each lot replace the traditional single tensile test for every 5000 pounds of material offered for delivery. Tensile tests are to be performed at stated periods, and are also to be performed whenever a lot is rejected for failure of the hardness requirements. Properly analyzed statistical data on the relationship between Rockwell hardness and tensile strength are apparently not yet available, and the specification limits had to be based on manufacturers' recommendations which were probably arrived at more or less empirically. However, the specification will provide for an extensive and important statistical study of this relationship, which will aid producers in maintaining quality control and will enable the Naval sampling plan to be put on a sound statistical basis. (This specification will be discussed again below in Section 7A.)

(3) *Formulation of probabilistic bases for ballistics tests.*

The traditional measure of the effectiveness of armor plate is the ballistic limit, which may be roughly described as the critical velocity at which a projectile of a given type will just barely penetrate the plate. The precision of this test (that is, its reproducibility) has always been open to question, not so much because of the difficulty of measuring the velocity of the projectile as because of the difficulty of estimating from a small sample of shots of various different velocities the "true" critical velocity of penetration. When to this testing error is added the very substantial variance due to nonuniformity of material, a rather strong case against the ballistic limit test can be built up.

An entirely different approach to the problem of ballistic evaluation of armor plate is furnished by the so-called "Per cent Through" test, in which the basic measure of quality is the *probability of penetration* of a given type of projectile at a given average striking velocity rather than the critical velocity of penetration. The advantages of the "Per cent Through" are that (a) the precision can be quite exactly evaluated in advance by the use of standard probability theory, and (b) the test itself

is much less complicated in practice and requires much simpler equipment. The chief disadvantages of the test may be that in general more shots must be fired to achieve a satisfactory discriminating power for the test than in the case of a ballistic limit determination. However, since the relation between the two types of ballistic criterion has not been fully explored, the definition of what could be considered comparable sets of statistical hypotheses for the two respective tests has not yet been formulated, and therefore it is impossible to decide when a "Per cent Through" test and a ballistic limit test are of equivalent discriminating power from the engineering point of view. The novelty, past achievements, and future possibilities of the test, as well as the central rôle played by statistical methods, seem to justify giving the story of the development of the test in some detail.

The chief use of the "Per cent Through" test to date has been in the testing of nonmetallic armor, and in particular, in the testing of a certain type of nonmetallic armor called "plastic protection". This material consists of stones or other hard objects imbedded in an asphalt mastic, with a steel backing plate. The extremely heterogeneous nature of the material renders a ballistic limit determination practically impossible, and in fact the very definition of what the true ballistic limit might mean in such a case is not easy to formulate.

By late 1942, the British had developed a test whereby armor-piercing bullets were fired point blank at zero degrees obliquity at a panel of the plastic protection, and the degree of penetration of the backing plate was assigned a rating in accordance with a prearranged system. The ratings thus obtained were recognized as being extremely variable and erratic, but it was apparently not realized that they could be very easily brought under control with a little statistical theory. This fact was pointed out by the Statistical Section of the Bureau of Ships early in 1943 in connection with the study of some extensive tests conducted by a manufacturer of roofing materials. A very satisfactory theoretical basis for the per cent of penetration observed when a given number of rounds of standard 30 or 50 caliber ammunition was fired at a panel with a given nominal striking velocity was found to be the law of probability which governs the appearance

of successes in repeated independent trials with constant probability of success in each. Since the rating of partial penetrations and bulges of the backing plate was somewhat subjective, it was agreed by all concerned that with proper mathematical support, a satisfactory quality characteristic for grading plastic protection would be the probability of any sort of penetration under given test conditions. The statistical problem of properly estimating the true probability from observed data was simply the classical one of determining the unknown parameter in a binomial distribution* from a sequence of successes and failures.

With this definition of quality, and with the test data at hand, it was possible immediately to issue a greatly improved purchase specification for plastic protection, containing a simple, foolproof, ballistic lot-acceptance test that any Naval inspector could easily perform at the plant of manufacture. It was also possible to make simple, accurate comparisons of different types of construction of the material.

At about the time that the theory for the "Per cent Through" test was being formulated, an important advance in sampling theory was being initiated and developed by the Statistical Research Group at Columbia University, working under contract for the Applied Mathematics Panel of the National Defense Research Committee. This development consisted of a sampling technique for testing statistical hypotheses known as sequential analysis, in which after each individual observation has been made (or after each conveniently chosen small group of observations has been made), a decision is framed as to whether to reject a given hypothesis, or to accept it, or to take further observations and suspend judgment for the moment. Earlier sampling methods had involved the selection of a preassigned fixed number of observations ("single sampling"), or at most two or three groups with a preassigned fixed number of observations in each.†

* The observed proportion P of "successes" in a given number of trials with constant probability p of "success" in each trial has a certain probability distribution called a binomial distribution. The only population parameter in a binomial distribution is p, which is the mean of the distribution. The observed proportion P is simply a special case of a sample mean. This can be seen by regarding each trial as an observation which has the value 1 if the trial is a "success" and the value 0 if the trial is a "failure"; P is then the arithmetic mean of a sample of such observations. The principles of inference presented in the Appendix, paragraphs 5-15 inclusive, are applicable without essential modification in the present situation.

† To avoid complications which were irrelevant to the main principles involved, the discussion in the Appendix refers only to single sampling.

The important feature of sequential analysis is that for a given discriminating power, sequential analysis requires a smaller average number of observations to reach a decision than any other comparable sampling technique. Since ballistic testing is destructive, and since panels of plastic protection afford convenient units for setting up step-wise test procedures, sequential sampling methods are particularly advantageous in the testing of this material. Sequential tests of plastic protection were accordingly devised for the plastic protection specification as soon as a verbal outline of the new theory was obtained from the Statistical Research Group; this is the first known commercial application of sequential analysis.

7. Process and Product Quality Control.

The field of material research and development discussed in the preceding section is contiguous to the field of quality control to be discussed in the present section. However, in the research field the problem is usually to compare one material (or treatment, or engineering method of test) with another, whereas in the quality control field, the problem is usually to compare a material or process with an absolute standard. The testing of statistical hypotheses plays an essential rôle in both fields, but in research, a rejected statistical hypothesis often means progress forward, while in quality control, a rejected statistical hypothesis may mean progress in the reverse direction.

A. The establishing of standards.

A prerequisite of quality control is to have a sound and workable definition of quality. This in turn means that not only must standard mean values of the various quality characteristics be set up, but also tolerances must be correctly determined which represent admissible and necessary ranges of variability. In other words, the band about the curve is here again just as important as the curve itself.

In establishing specification limits for a variable such as the tensile strength of half-hard brass rod, or the compression strength of certain type of brick, the methods of statistical inference have an important place. However, it is important to recognize in any discussion of the use of statistical theory in

determining specification tolerance limits that there are usually a number of factors of a nonstatistical nature involved. For one thing, practical considerations of procurement render it frequently advisable to set up the specification limits so that they will include the ranges of variability of many manufactures. Also, a specification must naturally depend heavily on the intended use of the material or piece of machinery. Thus engineering and economic considerations must be the final determining factor in the preparation of a specification. As Dr. Shewhart says in his valuable discussion of tolerances in reference (d), "It is not only what the engineer wants *but what he can get*, or at least get economically, that must be taken into account in the setting of tolerance limits". The rôle of statistical inference in the problem is essentially to tell the engineer what he can get.

It has been found that the following set of rules provides a useful guide to the solution of the problem of setting up specification tolerance limits for a given quality characteristic, such as a dimension, or a physical property, or an element of a chemical composition. (No pretense to completeness is made here, and the circumstances of different cases necessitate many deviations from the formula.)

(1) Obtain test data for material from as many of the prospective sources of supply as possible.

(2) Perform tests of statistical hypotheses to determine whether or not the means and/or dispersion of the data of the different sources of supply are significantly different. (If for example, the dispersions of all the sources of supply are not significantly different, then all the data for all sources can usually be pooled together for a more accurate estimate of a hypothesized common dispersion.)

(3) Estimate the key parameters affecting mean and dispersion, pooling together into each estimating function as much of the data as seems to be permissible in the light of step(2) and of related engineering considerations.

(4) By synthesizing the information obtained in (3) with knowledge as to the engineering requirements of the material and the procurement situation, establish allow-

able ranges for the mean and dispersion of any possible source of supply, and calculate therefrom the final tolerance limits.

In performing the steps outlined above, it is possible in certain cases to use laboratory data from research projects in which the primary object was originally to compare one material or treatment with another. An outstandingly successful example of this sort is furnished by the seam strength requirements in the Navy Department specification for pneumatic vest-type life preservers, in which the basic information for the tolerances was obtained from the designed experiment described in Section 6A, above.

However, a satisfactory test of the type of statistical hypotheses involved in research projects often requires a smaller amount of data than the amount needed to estimate population parameters with the accuracy necessary for specification purposes. Moreover, when the results of research are to be used as a practical yardstick which will be used day in and day out to measure the quality of purchased material, various manufacturing and testing variables are sure to enter into the picture which were not entirely foreseen in the research stage. It is well to emphasize in this connection that when a specification limit is being set up for some physical or chemical characteristic of a material, the population which must be studied is the population of apparent values of the characteristic as revealed by test data. Thus the dispersion of the population must include the component due to the error (or lack of precision) of the test, which in routine inspection is likely to be greater than in a laboratory experiment. Therefore in many cases the only practicable way of setting up tolerance limits in accordance with the rules given above consists in taking sample units from the current production of several reliable manufacturers and putting these units through the proposed tests in a manner which seems to be representative of the way in which routine inspection tests will be conducted.

Statistically based tolerance limits derived from routine inspection test data were written into a large number of Navy Department purchase specifications during the war. Some of the ma-

terials covered by these specifications were: heat treated glass, fiber glass, resistance wire, electric cable, electrical insulation of various types, chemical compounds, refractory materials, rubber products, meters and measuring devices, insecticide dispensers, wood products, rope and yarn, various plastics, life saving devices, electronic equipment, and many different metallurgical materials and products. Consideration of space prevents discussing more than a very few examples. These have not been chosen with the view of presenting somewhat orthodox illustrations of the systematic procedures for setting up specification requirements given above, but rather with a view of presenting somewhat extreme cases which may serve to emphasize the many practical problems involved in arriving at successful standards.

A good case to start with is the history of the kapok-jacket life preserver, in which refined statistical methods of deriving tolerances were not employed in the original specification. This life preserver consists essentially of a heavy cotton drill jacket into which are sewed several pads stuffed with a buoyant medium. The main test for this life preserver is a sample pad buoyancy test, in which the buoyancies of the pads after 24 hours immersion in water are measured. The supply of pure Java kapok for the buoyant medium was cut off at the beginning of the war, and stocks in this country were necessarily mixed with Ecuadorian and reclaimed kapok which had unknown, but inferior, buoyancy properties. To obtain minimum requirements, a Navy Yard ran buoyancy tests on several pads stuffed with various grades of mixed kapok. The mean buoyancy was thereupon calculated, but unfortunately the dispersion of the data seems to have been either estimated incorrectly or totally ignored. In any case, an arbitrary quantity of one pound seems to have been subtracted from the observed mean values, and the results were submitted to the Bureau of Ships as the recommended minimum buoyancy values. Since the standard deviation of this buoyancy test, as determined subsequently from production test data, was about ¾ pound, and since the specification contained a fairly "tight" sampling plan, serious trouble immediately resulted when the specification was put into use. A temporary blanket waiver of buoyancy requirements was soon issued, as the procurement situation was extremely urgent. However inspection tests were

continued in exact accordance with the specification and the data were submitted periodically to the Navy Department for study. In addition, the cooperation of the Naval Inspection Offices was secured to maintain statistically based control charts in the manufacturer's plants, on which buoyancy data were plotted on a day-to-day basis to assist the manufacturer in obtaining quality control. This type of quality control project is discussed more fully in Subsection B below.

After about two months of fact-finding, during which the manufacturers became quite quality-control conscious and the product was considerably improved as to average quality and uniformity, it was possible to issue statistically based minimum buoyancy requirements which were realistic and enforceable. The statistical techniques employed in deriving the new tolerances were relatively simple, and involved little more than calculating the average of the standard deviations of the various manufacturers and looking up the appropriate factor to apply to the average in a table of the normal curve. But the result was a 20 per cent decrease in the old minimum buoyancy values. Even with improved manufacturing control, about 7 per cent to 10 per cent of the pads of the better manufacturers fell below the old requirement, and any reasonably tight lot acceptance sampling plan would have rejected practically every lot of certain manufacturers.

It is worth while to digress here for a moment on a technical point, to anticipate the discussion of rational sampling which will be given subsequently. After determining that 7 per cent to 10 per cent of the individual pads should be allowed to fail the old requirement, it would have been quite possible to set up a sampling plan which would nearly always accept the product if this "process average" were maintained, and would nearly always reject a lot in which, say, 30 per cent of the pads were failures. These conditions would be satisfied, for example, by a plan in which 20 random sample pads were selected from each lot and the lot were to be accepted as to buoyancy if 4 or less failed to meet the requirement, and otherwise were to be rejected. However, a study of the actual variability of the material would still have been necessary, to enable the purchaser (here the Navy) to get some idea of just what he was really buying. In other words, just how bad were the individual pads in the allowable

10 per cent? To obtain information of this sort, which is essential to the engineer who is responsible for the design and performance of the equipment, it would have been necessary to conduct the same statistical study as was employed to re-set the tolerances of the specification. In the case of quantitative requirements in a specification it usually seems to be the best course for all concerned to display genuine minimum or maximum numerical requirements in the specification, rather than to publish overly tight tolerance limits which are made practicable by lenient acceptance provisions.

Yet in the case of the Joint Army-Navy specification for desiccants, various considerations forced the adoption of the latter course. The story of this specification illustrates a number of typical aspects of the problem of setting up Government purchase specifications.

The chief quality characteristic of a desiccant is of course the moisture adsorption capacity of the material at various relative humidities,—a property which lends itself fairly readily to routine laboratory determination. Prior to the preparation of the Joint Army-Navy specification, the Government had been maintaining a number of specifications in the field for various types of desiccants. These specifications all had differing requirements, and were sponsored by various purchasing activities. One feature which the specifications did have in common was that apparently the moisture adsorption capacity requirements had in no case been set up in accordance with sound statistical principles, but had been evolved out of the usual admixture of manufacturer's recommendations, older specifications, presumed end-use needs, and guesswork. The recommendations of a certain large and reliable manufacturer of silica gel had received especially heavy weight.

The same empirical methods were used to fix the minimum moisture adsorption requirements in the new specification. They were arrived at in a series of conferences of the cognizant technical personnel of the two services, and when the specification arrived in the Statistical Section of the Bureau of Ships for insertion of inspection clauses (see subsection B below), the design requirements and methods of test were in supposedly final form. To formulate a rational sampling plan, it was necessary to

evaluate the statistical significance of the tolerance limits. However, a search for Government inspection test data to use for such a purpose revealed that there were none available. At this point several producers of silica gel, including the large one dominating the scene, volunteered to provide masses of their own production control test data. These data were analyzed, and the rather surprising result was obtained that the applicable moisture adsorption capacity tolerance limits in the new specification (and in the old ones too) were not at all in accord with the data. They were much too severe at the important low and intermediate relative humidities, and very loose at the high humidity values.

The question now was this; should an attempt be made to secure the agreement of the various Bureaus and agencies concerned to have the moisture adsorption values changed in the specification, or should the sampling plan be set up so as to allow for a certain substantial percentage of nonconforming material? For better or for worse, the latter course was followed and a sampling plan which merely insures that not less than 80 per cent of the material will be in conformance with the specification was employed. The reasons were that (a) agreement on the tolerance limits by all interested parties had already been reached, and the need for immediate consolidation of the diverse old specifications was so great that the delay of several months which arriving at a new agreement would entail seemed quite undesirable, (b) the material had enjoyed a history of fairly steady improvement, and a tight specification in the critical humidity ranges might act as an incentive for further progress in this direction, (c) no data at all on other types of desiccants than silica gel seemed to be available, so that a very tight sampling plan for these desiccants seemed to be inadvisable until a further study of their properties had been made, and it was desirable to publish only one sampling plan for all types of desiccants covered in the specification if possible.

This example brings out the fact that while many nonstatistical considerations must enter into the writing of specification requirements, nevertheless, statistical analysis may be indispensable for the intelligent interpretation of a specification arrived at nonstatistically.

Another example in which the published specification values were not consistent with the information obtained from a statistical analysis of production data is the case of the new specification for naval wrought brass, previously mentioned in Section 6 above. The classical test for this type of material is a tension test in which yield point, ultimate tensile strength, and elongation are all measured. To assist in the revision of the old specification, an elaborate statistical study of tensile test data on half hard brass rod manufactured under the old specification by four large brass mills was undertaken. The analysis showed that various mills were about alike as to mean values and dispersions, and that each one had been presenting a substantial amount of material which was not in conformance with the requirements of either the old or the proposed new specification. A segment of the data is shown in Figure 6. Rejection under the old specification apparently had been avoided because of the weak sampling and retest provisions in the specification. If production were to continue at the present quality level, the inference from the analysis was that in the smaller sizes, as much as 30 per cent of the product of the better manufacturers would fail to conform with the proposed new specification as to tensile strength, or yield point, or elongation, or some combination of these requirements. In the larger sizes, the specification limits were very loose.

Now the proposed new specification had been prepared by an aggressive and competent engineer who had had many years' experience in the brass industry. This engineer had succeeded in securing the approval of the industry for a large number of proposed alterations in the old specification which had resulted in a far more accurate definition of what was wanted than the old specification had previously provided. For example, chemical composition requirements had been tightened up, Rockwell hardness requirements had been added, and testing procedures had been brought into agreement with current mill practices.

When this engineer viewed the results of the statistical analyses of the past data, which indicated that a considerable modification of the proposed tension test limits was in order, he at once raised strenuous objections. He stated that (a) the material which would be offered under the new specification as half-hard

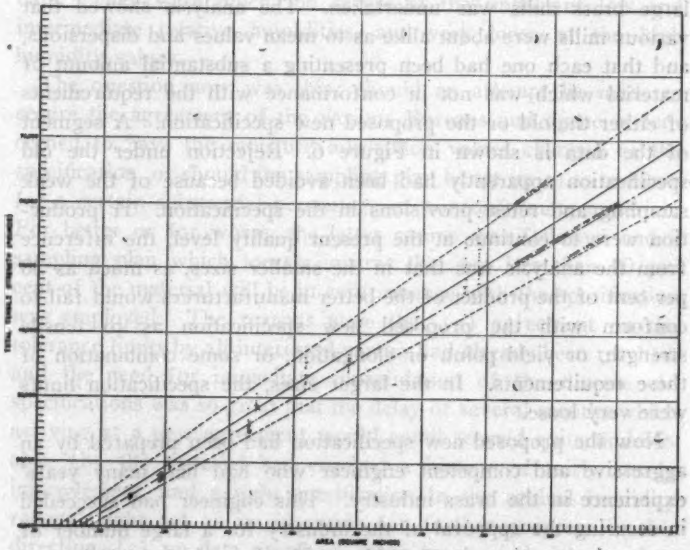

FIGURE 6.

TENSILE STRENGTH OF HALF HARD ROUND BRASS ROD.
MATERIAL OF 6 DIFFERENT MANUFACTURERS PRODUCED IN 1944.

and hard brass rod (the type of material which formed the basis of the statistical analysis) would be quite different from what it had been under the old specification because the chemical composition requirements had been defined more clearly, and (b) anyhow even under the old specification, the manufacturers could have met the tension test requirements if they had really wanted to do so, by alterations in composition and mill practice.

Statistical analysis of historical data furnished no answers to engineering objections of this kind. Translated into statistical language, the engineer had denied the stability of the causal system underlying the statistician's hypothesized probability distribution, and if this denial was valid, then (as stated in Section 3) no useful inference could be derived from the sample data at hand.

Since the new specification as formulated by the engineer was known to be better than the old one in so many ways, and since no inspection test data on material produced to the new requirements would be available for some time, it was accordingly decided that the results of the extensive statistical analysis of tension test data taken under the old specification should be ignored, at least for the time being. The nonstatistically derived tolerances are enforced in the specification with fairly tight sampling inspection procedures. At this writing, the specification is not yet out in the field, so the wisdom of this decision is not yet known.

B. *The enforcement of standards.*

Any purchasing activity such as the Navy which is engaged in procurement on the grand scale has a never-ending problem of securing compliance with standards on the part of vendors. The problem is aggravated in the case of a Government agency by the fact that vendors who claim ability to meet the design requirements cannot be selected on the basis of quality and dependability; in theory, at least, the lowest bidder gets the contract. The traditional device employed by Government agencies to meet this situation has been the maintenance of a force of inspectors and testing laboratories whose duty it was to ascertain the quality of the material offered for delivery.

But for economic reasons each local unit of an inspection

force must be prepared to cover such a broad field of engineering that it is usually impossible to assign a specialist to every inspection job; and even the most experienced inspector of, say, ferrous metallurgical material cannot be expected to keep up with the latest methods of sampling and tests for all items under his cognizance. On the other hand, the bidder on a contract frequently needs to have some idea of what methods of enforcement are going to be used before he can arrive at an intelligent cost estimate.

It has therefore become customary to supplement a standard with specific written instructions as to how compliance with the standard is to be ascertained. Accordingly, purchase specifications now contain requirements of two very different types. The first type of requirement is the type which has been under discussion in subsection A above. Requirements of this type are frequently called *design requirements;* they define the dimensions, physical and chemical properties, and performance characteristics which the purchaser desires in the material, so that it will be satisfactory for its designed use. The other type of specification requirement is concerned with the enforcement of design requirements. Requirements of this type are called *acceptance requirements.* They consist of definitions of the amount and nature of evidence considered necessary to establish that material supposedly produced to the design requirements actually complies with them to a satisfactory extent. Acceptance requirements may be conveniently grouped into two classes:

(a) *Sampling requirements* (including as a special case the requirement of 100 per cent inspection). These comprise the administrative procedure whereby the material is accepted or rejected.

(b) *Methods of test.* These comprise the analytical engineering procedures which provide the factual basis for the administrative procedure.

In the typical Government specification, design requirements and acceptance requirements are often included in the same leaflet.

The task of enforcement of standards has fallen into two main channels: the preparation and application of scientific sampling requirements for the acceptance requirements portion of specifi-

cations, and the routine analysis of inspection data to assist the manufacturer to maintain quality control.

(1) *Preparation and application of scientific sampling requirements in specifications.*

From the standpoint of the theory of statistical inference, a statistically based sampling inspection plan consists of a test of a simple statistical hypothesis, designed so as to have a predetermines discriminating power. The hypothesis to be tested is that some parameter measuring a quality characteristic of the population of material under inspection lies in a range of values which represents definitely "good" quality, and the alternative hypothesis is that the parameter lies in a range of values which represents definitely "bad" quality. The principles are quite completely illustrated by the discussion of testing statistical hypotheses given in connection with the cylinder example in the Appendix, paragraphs 8-12 inclusive. In sampling inspection work, the risks of erroneous decisions in testing statistical hypotheses are given descriptive names: the probability of accidentally rejecting a "good" lot (called the "significance level" of the test in the Appendix, paragraph 11) is called the "producer's risk", and the probability of accidentally accepting a "bad" lot is called the "consumer's risk".

As in all practical applications of the theory of tests of statistical hypotheses, the definition of what is "good" and what is "bad" material, and the setting of the consumer's and producer's risks, are in any given case rather arbitrary, and are affected by numerous subjective and economic factors. Indeed, the fundamental problem in writing acceptance requirements is an equilibrium problem in economics: balancing the cost of inspection with the expected loss to the producer due to accidentally accepting subspecification material. This problem has many administrative and psychological aspects. But the statistical theory makes a very great contribution to the solution of the problem by controlling the sampling errors; and it provides thereby a sound basis for a rational administrative decision.

To date, the sampling requirements in approximately 1000 new purchase specifications, or revisions of old purchase specifications, have been reviewed. Most of these have been Navy Department

specifications, but there have been a number of Joint Army-Navy specifications also. Statistically based inspection plans have been placed in about 400 of these. In the remainder, some form of 100 per cent inspection or purposive sampling has been specified. Materials for which statistical acceptance requirements have been formulated include life saving equipment, glass products of many varieties, chemical compounds, electrical components, rubber products, metallurgical products, rope, twine, instruments, clothing items, etc.; in short, they cover the whole range of procurement necessary for the building and maintenance of ships.

The program has included a vigorous follow-up campaign in the field, to insure understanding of, and compliance with, the new acceptance requirements on the part of Naval inspectors and manufacturers.

There appear to be two outstanding results of this activity. The first of these has been a notable "tightening up" of inspection procedures under the specifications with statistically based sampling inspection plans. The second consists of a general improvement in the all-around quality of the specifications.

The improvement in the work of the field inspectors under the affected specifications seems to have been not so much due to the particular mathematical characteristics of the various sampling plans in these specifications, as to the fact that Government inspectors and manufacturers alike recognized that they had been rationally, and not arbitrarily, chosen, and that the numbers displayed in them really mean something. The irrational plans of older specifications had been very frequently ignored in the field by inspectors who instinctively recognized their weakness. After hearing an explanation of the purpose and construction of a statistically based plan (and incidentally after thus ascertaining the Bureau's interest in the proceedings), few inspectors have desired to take on the responsibility of waiving or modifying the specified inspection procedures without formal authorization from the Bureau.

The cooperation of the Government inspectors has been obtained not only because of their recognition of the advantages to the Navy of the new sampling clauses, but also because these specifically stated acceptance requirements frequently simplify their duties and clarify their responsibilities. Great care has

been taken to adopt a standard editorial form for the acceptance requirements of the specification prepared under the program, so that the inspector can easily find his way around in the specifications. Then too, the acceptance procedure in each case is more or less completely detailed in the specification, and the level of inspection (that is, the power of the sampling plan) is also completely specified, all of which relieves the inspector of the necessity of making troublesome decisions and assuming unwanted responsibility. And finally, there have been a number of cases where the use of scientific sampling methods has materially reduced the amount of inspection. If, for example, an old specification used to require the inspector to sample one item in 50, the new specification might contain a sampling plan consisting of taking 10 sample items from each lot of 1000 and rejecting the 1000 if any one of the 10 were found to be defective. The second plan is far "tighter" than the first but it requires fewer samples. It is also advantageous in some cases to use sampling inspection where 100 per cent Government inspection had previously been required. The chief reason for this statement, aside from the savings in the cost of inspection, is that in 100 per cent inspection only individual nonconforming items are rejected, but in sampling inspection, rejection is on a lot basis, and a rejected lot may contain a large proportion of conforming material. The threat of lot rejection is a powerful incentive to a contractor to inspect material properly before presenting it to the Government inspector.

In connection with the problem of obtaining good inspection, it is perhaps worth mentioning also that a situation at the Bureau level which had frequently resulted in lax inspection in the field is also in the process of being remedied. When material has been placed on the "Navy Department Acceptable List of Approved Materials", by passing some precontract tests, the Naval inspector is permitted at his discretion to waive routine tests on it. In the opinion of the writer, the "Acceptable List" has been greatly overrated as a tool of quality control, because there often seems to be little reason to believe that a vendor will maintain, when in production, the quality of a precontract sample which he had made up and sent in for the approval tests. As recognition has become more or less general in the Bureau

of Ships that scientific lot inspection procedures are now available which give the Navy a much more substantial measure of protection than had heretofore been enjoyed, the use of the "Acceptable List" for quality control purposes has declined. In those specifications which still do carry qualification clauses, rational lot acceptance plans and production check tests have been regularly inserted under the specification sampling plan program of the Statistical Section, just as if the material did not have to be on the "Acceptable List". Inspectors have in general carried out these plans faithfully in spite of the waiver option.

As stated above, the second outstanding result of the specification sampling plan program is that the all-around quality of the specifications (that is, their accuracy, consistency, and logic) has been elevated. This result is one that was not anticipated at the inception of the work. Both the design requirements and the methods of test sections of the specification have been affected. This improvement has come about because of what might be called the *a priori* information necessary to install a rational sampling plan, and also because of the *a posteriori* information which is automatically obtained when a sampling plan has been installed.

In the introductory paragraph of Section 6 above, it was stated that one of the most important contributions of the statistical doctrine of experimental designs to a research program lies in the fact that before it can be employed in setting up an experiment, the engineering aims of the experiment must be clearly defined. Since a statistically based sampling inspection plan is a special case of a designed experiment, the remark holds true in the present case. In other words, before a systematic procedure for collecting evidence that material conforms with design requirements can be written out, there must be a very clear-cut and consistent statement of just what these design requirements are. Furthermore, in order to arrive at the proper definition of a "good" and "bad" lot, there must be factual information at hand as to the significance of the tolerance limits and other quantitative requirements in the specifications with respect to the capabilities of current sources of supply.

These facts were recognized from the outset of the work of the Statistical Section on sampling clauses in specifications, and

in each specification which was processed the design requirements and methods of test were subjected to analysis and appraisal before the sampling clauses were formulated. The least important results were that many minor contradictions and omissions were picked up and corrected. The major results were that many fact-finding expeditions were organized which in some cases resulted in drastic improvement of specifications, and in one or two cases resulted in their complete withdrawal. Just as inspectors in the field cannot be expected to be specialists in each field of engineering, so the materials engineers in the Bureau cannot in general be expected in the rush of wartime procurement to have a close familiarity with all the items under their cognizance, especially since they are frequently too busy to do much traveling to witness methods of manufacture and inspection.

But due to extensive waivers of inspection in the field, and also due to the fact that early in the war a directive had gone out to Navy laboratories relieving the laboratories of the necessity of forwarding quantitative data on accepted samples to cognizant inspectors, attempts to obtain factual information on the statistical significance of design requirements all too frequently met with failure. In many cases, there seemed to be no reliable information as to variability of material available anywhere; manufacturers themselves, although generally cooperative, had never kept the necessary records.

In numerous cases where no *a priori* information was available, it was necessary to issue the specification anyhow, and make arbitrary assumptions about the statistical significance of the tolerance based on the judgment of the engineers concerned. Many of these specifications have worked out satisfactorily in practice. But in quite a number of cases, the data which were automatically obtained from the operation of statistically based sampling plans revealed totally unsuspected inconsistencies and impracticabilities in design requirements, and resulted in radical changes in specifications. An outstanding example of this sort has already been discussed in subsection A above (the case of the kapok life jackets). There have been many other similar cases.

The work on sampling requirements described in the preceding

paragraphs was partially responsible for some recent important activities of the Inspection Administration of the Navy in connection with the preparation of the Navy Sampling Inspection Manual (reference (e)), consisting of sampling inspection methods for the use of Naval inspectors. The manual was prepared on contract for the Inspection Administration by the Columbia Statistical Research Group, a subcontractor of the Applied Mathematics Panel of the National Defense Research Committee. The manual contains both explanatory material and a comprehensive set of tables. It seems to be by far the finest and most complete manual on acceptance sampling ever written. Unfortunately, it was not completed until the closing days of the war, and never really saw action in the field.

(2) *Continuous quality control studies.*

While a set of scientific lot acceptance sampling clauses in a specification is a powerful tool for the enforcement of design requirements, in many situations the control of quality of accepted material can be greatly improved by subjecting the inspection data obtained therefrom to a continuing statistical analysis. The results of this analysis may be used both to guide the manufacturer on a current basis and to strengthen the accuracy of the purchaser's appraisal of quality through accumulative evidence. Indeed, when the procurement situation forbids lot rejections (as is all too often the case in time of war), or when a specification is under development, or does not contain scientific acceptance requirements, the *only* recourse of the purchaser is to analyze what inspection data are avaliable, and to discuss the results of the analysis with the manufacturer over the conference table.

As experience accumulated under the rational sampling program it was realized that the contribution of sampling inspection methods to quality control was far less dependent on exactly which plan is chosen in any particular instance (provided that the plan is not hopelessly weak), than on how assiduously the chosen sampling plan is followed up by the proper processing and distribution of inspection data. Accordingly, the Sampling Inspection officers in the field Naval Inspection Offices (who had been appointed in the spring of 1945 to oversee the operation of the Navy Sampling Inspection Manual), were repeatedly urged

by letters from the Bureau to install quality control charts wherever applicable on all inspection assignments of interest to the Bureau of Ships, and in particular, on all inspection jobs under statistically based specifications.

Some notable examples of quality control by chart methods resulted from this request. One example, that of the kapok life jackets, has been cited in Subsection A above. Other examples which deserve special mention are (1) the set of control charts maintained by inspectors all over the country on seam strengths of pneumatic life preservers; (2) the set of control charts for surface inspection of china mess gear maintained by the San Francisco inspection office.

Requirements relating to the installation and maintenance of quality control charts have also been formally written into certain specifications as part of the inspection procedure. The outstanding example of this type is the specification for the filling of insecticide dispensers. The discriminating power of the sampling provisions in the specification was restricted by the fact that whereas the tremendous rate of production (the assembly lines in each plant were filling 15,000 dispensers a day) and lack of storage space of the contractors rendered frequent acceptance decisions mandatory, nevertheless for reasons of economy of materials and inspection manpower, relatively few sample dispensers could be tested each day. Only four sample dispensers were used in the part of the lot acceptance plan which was concerned with weight of fill; but the specification explicitly requires the Naval inspector to set up and maintain a control chart for this variable, to keep the chart in a conspicuous place, and to invite the attention of the contractor whenever the chart revealed any dangerous trends or lack of control.

The results of applying these instructions to a specific contractor are shown in Figure 7. This figure represents the data for the first two months of operation under the control chart procedure. The figure tells its own story as to the effectiveness of the statistical control chart as a tool of inspection and management. Both the contractor and the Naval inspector who kept the chart were much interested in the revelations of the chart, and traced down and corrected assignable causes of variation until a very satisfactory state of control was reached. Incident-

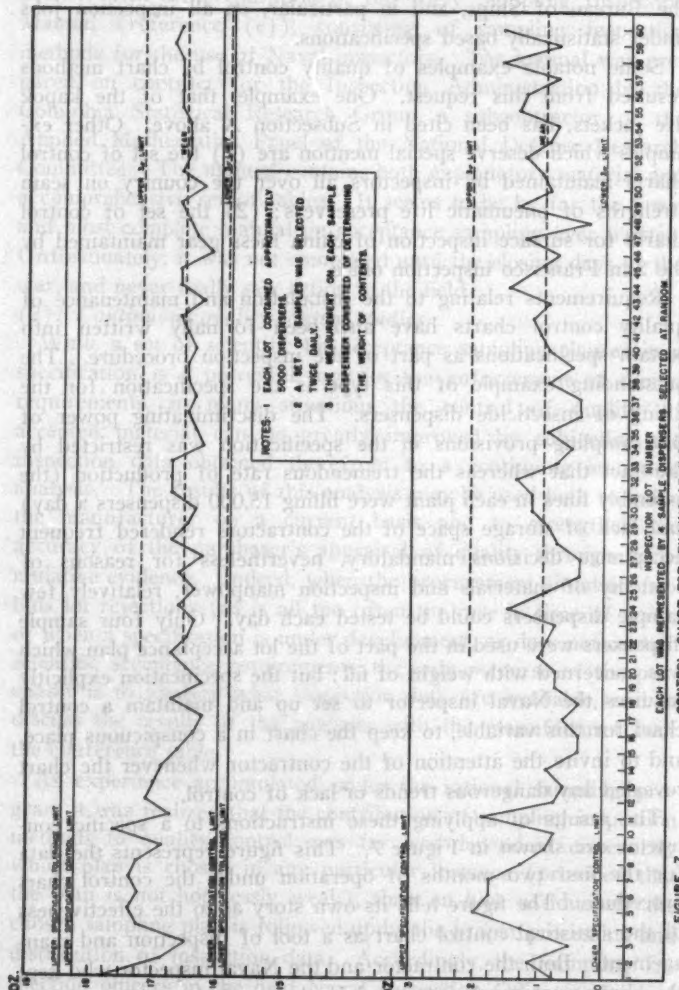
NOTES: 1 EACH LOT CONTAINED APPROXIMATELY 5000 DISPENSERS.
2 A SET OF SAMPLES WAS SELECTED TWICE DAILY.
3 THE MEASUREMENT ON EACH SAMPLE DISPENSER CONSISTED OF DETERMINING THE WEIGHT OF CONTENTS.
MEAN
RANGE
INSPECTION LOT NUMBER
EACH LOT WAS REPRESENTED BY 4 SAMPLE DISPENSERS SELECTED AT RANDOM.

FIGURE 7.

CONTROL CHART FOR FILLING OF INSECTICIDE DISPENSERS

ally, the inspector was a young woman with no previous experience in statistical methods of quality control.

8. Conclusion: The Rôle of the Engineer.

The preceding sections have cited numerous more or less successful applications of the methods of statistical inference to problems of engineering. In each case the basic contribution of the statistical methodology has been to assist the user to acquire knowledge about a fundamental, but not totally evident, causal system which underlies the observed data and which might produce similar data in the future. In other words, the interest has never been in the set of data at hand, but rather in what produced it.

It is all too easy in any exposition of this type to overemphasize the contribution of statistical methodology at the expense of the really essential and basic rôle of engineering knowledge. Given any set of numbers, a statistical computer can always sit down without any idea whatsoever of the pedigree of the numbers, and after going through a set of complicated computations, he will come out with some numerical averages and measures of dispersion which are theoretically estimates of population parameters. Obviously the estimates calculated by the computer are completely worthless unless there is some underlying theory as to what the estimates are supposed to estimate. In other words, the whole meat of an engineering statistical problem is in the basic assumptions and hypotheses. *These are essentially in the province of the engineer.* He may need the help of a professional statistician in formulating his problem in terms of statistical hypotheses, and in specifying appropriate forms for general underlying distributions, and he will certainly need professional advice in the technical details of processing data for statistical tests and estimations. But when the machinery of statistical inference has been explained to the engineer and put in working order, he is the one who must turn the knobs and make the settings.

For example, in lot acceptance sampling plans, it is the job of the engineer to formulate the definitions of "good" and "bad" lots, and to specify the risks of rejecting the one and of accepting the other. In the setting of tolerance limits for specifications,

CONTROL CHART FOR FILLING OF INSECTICIDE DISPENSERS

FIGURE 7.

the engineer must have the last say in defining permissible ranges of variation, after due account of necessary variability has been taken.

Most particularly, in research and development problems, where the fundamental rôle of statistics often is to point the way rather than to give final answers, it should never be pretended that statistical analysis is a substitute for controlled laboratory experimentation guided by properly formulated physical or chemical theory. In other words, good statistics will never come up bad engineering.

A wartime experience which must necessarily be reported here in only vague terms will serve to illustrate this point. In the early days of the war, a Navy Department contract was let out to an educational institution to study the action of a certain type of nonmetallic armor. The persons assigned by the contractor to the work immediately recognized that current tests required sound statistical theory as a basis, and devoted themselves mainly to the formulation and exposition of this theory—a project which was essentially in the province of the professional statistician and not in that of the physicist or engineer. Unfortunately the improvement of the material was essentially dependent on the development of a suitable physical theory of its operation, and this type of question received little attention from the contractor's personnel. Over a year after the contractor's report had been completed, the appropriate physical theory was arrived at empirically by engineers in the Navy Department and in private industry, and a tremendous increase in the effectiveness of the armor was immediately obtained as soon as certain simple consequences of the theory were tried out.

APPENDIX.

Further Discussion of the Statistical Background.

1. It is the purpose of this Appendix to illustrate and amplify the brief sketch of the principles of statistical inference given in Section 3. The exposition will be nonmathematical, but it is hoped that a careful reader may be able to obtain some fairly definite ideas as to the problems and techniques involved.

2. The discussion will be built about the simple practical exam-

ple which is the basis of Figures 1, 2, and 3. During the war, a small cylinder for dispensing an insecticide in the form of an aerosol was being manufactured in large quantities. Partly because of the method of test, and partly because of the method of manufacture, the apparent volumetric capacity varied somewhat from cylinder to cylinder, although the cylinders were all supposed to be alike. For a quality control study, a random sample of 1800 of these cylinders was selected from the first 100,000 and their volumetric capacity was determined. To apply the methods of inference to this sample, the first step was to postulate the general form of the distribution of the volumetric capacity in the population (which could be regarded as either the static population of 100,000 cylinders from which the samples were drawn or the population of all such cylinders that had been, and were to be, manufactured). For various reasons, but chiefly on the basis of experience with similar situations, it was assumed that the theoretical frequency distribution of the volumetric capacity (in this case, the distribution of relative frequencies in the population of cylinders) was of the so-called "normal" or Gaussian type, which is the type of distribution defined by the equation (1) in Section 3.

3. Good sample estimates of the parameter μ and σ of this distribution are known to be the arithmetic mean and standard deviation of the sample data; the error in these estimates is ordinarily quite negligible when the sample contains as many as 1800 observations. These estimates were accordingly computed and the theoretical distribution was set up on the assumption that the estimated values were exactly equal to μ and σ. The result is shown graphically in Figure 1, where the area under the curve over any interval on the horizontal axis represents the probability, or theoretical relative frequency, assigned to that interval. The probabilities assigned by the theoretical distribution to various ranges of the volumetric capacity agreed quite well with the corresponding relative frequencies in the sample data, so it was judged that the specified form of the distribution was satisfactory.*

* This judgment was assisted by a test of "goodness of fit" of the theoretical distribution of the observed data called by statisticians the "Chi-Square Test". However, the exact nature of the hypothesis tested by this test and the function of the sample data used are both too complicated to discuss here.

4. It is to be observed that the theoretical frequency distribution, as so set up, provides direct answers to certain questions which are highly important from the point of view of both the manufacturer and the purchaser. The first of these concerns the mean capacity. By comparing the value of the population mean shown in Figure 1 with the nominal capacity which had been specified and ordered, a judgment can be formed as to whether the present methods of manufacture produce a satisfactory product on the average. But for many purposes, as previously indicated in the Introduction, the really vital question is that of the *range of variability* which must be allowed for in using the cylinder* and in writing a practical specification for it. As shown in Figure 1, under present conditions of testing and production, all but about 1 per cent of the cylinders can be expected to have volumetric capacities lying in a range of $\pm$ 5 cc. about the mean. This is a range of 2½ times the standard deviation of the distribution.

5. The cylinder example will now be used to demonstrate the principles of estimation and of testing hypotheses in the important practical case in which only a few sample cylinder (not 1800, as before) are to be used. Suppose that there is a possibility that the manufacturer may inadvertently (or advertently) change the mean volumetric capacity of the cylinder by a slight change in the method of manufacture. Suppose further that it may be assumed that no change will occur in the control over the manufacture, or in the method of test, which would result in a change in the form of the theoretical distribution or its dispersion. What is the best way to estimate the new mean, or at least to establish conclusively that a shift has occurred, using a random sample of as few observations as possible?

6. To answer this question, it is first necessary to study the theoretical distribution of the sample mean, because this is the obvious function of the sample data to use for the job of calculating or testing; and when only a few observations are involved, the sample mean will exhibit random fluctuations of magnitude

* In the present case, this happened to be particularly important, because the cylinder was filled with the aerosol by an automatic process, which could not be readily adjusted to slight variations in the volumetric capacity. It was necessary for consideration of safety to set the filling process so as to avoid overfilling the undersized cylinders, while at the same time it was obviously desirable to put as large a charge into each cylinder possible.

comparable to those of a single observation. This distribution is very easily obtained from standard formulas of mathematical statistics. For the case of a sample of 4 observations, it is illustrated in Figure 2. If the sample consisted of 8, or 10, or 50 observations, the curve shown there would be relatively much more peaked and would cover a much smaller range—a phenomenon more familiarly known as the "law of averages". If the sample consisted of only 1 observation, the curve of Figure 2 would be identical with that of Figure 1.

7. The problem of estimation may now be easily solved. A glance at Figure 2 will reveal that the probability that the sample mean falls in a range of $\pm$ 2 cc. about the population mean is about 94.6 per cent. But another way of saying this is to state that a range of 2 cc. about the sample mean would, in repeated sampling, cover the population mean about 94.6 per cent of the time. An interval whose endpoints are computed from sample data which covers an unknown population parameter with a given degree of certainty is called a *confidence interval.* Thus the interval $(\bar{x} - 2, \bar{x} + 2)$, where $\bar{x}$ denotes the sample mean, is a *confidence interval* for the unknown population mean, corresponding to a probability or *confidence coefficient* of 94.6 per cent. If this confidence interval is too wide to serve as a practicable estimate, it can be narrowed without decreasing the confidence coefficient by appropriately increasing the number of observations in the sample.

8. But in many cases the actual estimation of the value of the new population mean itself would be of less practical importance than the detection of the mere fact that there has been a significant shift in the population mean. To this end, the way to proceed is to make the hypothesis that there has been no shift at all, and that the population mean is still at its old value. This hypothesis can then be tested as follows: A sample of some fixed number of observations, say 4, is drawn and the sample mean calculated, exactly as in the problem of estimation. If this sample mean falls into a certain "critical region" lying in the outer reaches of its probability distribution (for instance in the situation illustrated in Figure 2, if the sample mean falls, say, more than 2 cc. from the assumed population mean), then the hypothesis of no shift is rejected; and it is presumed that there

has been some shift in the population mean. The argument for rejecting the hypothesis is that if it were true, a most improbable thing has happened.

9. This simple formulation of the procedure of testing statistical hypotheses is seemingly independent of the sample size (that is of the number of sample observations). In its general form, it is used extensively in agricultural and biological experimentation, where the number of sample observations obtainable is frequently governed by economic considerations and the difficulty of obtaining stable conditions. But it is often inadequate for engineering purposes, because it ignores the power of discrimination of the test—that is, in the present case, the degree of certainty with which the test will detect a change of a given preassigned magnitude in the population mean. In other words, this simple set-up provides a test which will protect the user against incorrectly concluding that some change has occurred when it really has not; but it will not provide for a preassigned degree of protection against *failing* to find a change which has *really occurred*. To provide this additional protection—that is, to take into account the power of discrimination of the test—it is necessary to consider the sample size, which therefore enters the picture once again.*

10. There are two convenient ways to give an answer to the question of the discriminating power of a test. The first way consists in drawing "power curves" of various tests, which in the present case of the cylinders would indicate for various given sample sizes the different probabilities of rejection of the hypothesis of "no shift" corresponding to different true values of the population mean. The test having the required discriminating power could then be chosen from inspection of these power curves; but before making the choice, *it would be necessary to define more or less exactly the size of shift in the population mean which the test should surely detect*. This leads to the second and simpler way of taking power into account, which consists in starting with the definition of the size of the shift in

* The question of accuracy, or power of discrimination, is discussed at some length both here and in Section 3 because if the reader wishes to pursue the study of the principles of statistical inference further, he will almost surely wish to consult the two modern classics of applied mathematical statistics by R. A. Fisher (see par. 27 below), and unfortunately neither these books nor their many descendents cover the matter adequately.

the population mean which is really significant from a practical point of view, and then by trial and error (or by solving what is in the present case a very simple equation in which the sample size is the unknown) setting up the test which will decide with suitably small chances of error whether or not a change of the specified magnitude has occurred. There is an important implication here, which was also hidden between the lines in the preceding discussion of estimation by interval. It is that before the observations are actually made the experiment must be *planned* or *designed* so that it will yield the information it is supposed to yield.

11. To demonstrate this procedure, suppose that in the case of the cylinders it was decided that some action should almost surely be taken if a decrease of 3.5 cc. or more were to occur in the mean volumetric capacity of the cylinders, but that if the mean remained at its present value or were increased, no action was desired and the probability of erroneously taking action should be minimized. As is shown in Figure 3, these conditions will be satisfactorily met by a test which consists in rejecting the hypothesis of *no change* if the mean of a random sample of 4 observations falls more than 2 cc. below the boundary of the permissible range of the population mean. If the hypothesis of *no change* or an upward change were true, the chance of erroneously rejecting it is not more than 2.3 per cent, and if the hypothesis of a change as large as 3.5 cc. were true, the chance of not finding out that something had happened is not more than 6.7 per cent. The value 2.3 per cent is called the *significance level* of the test.

12. Of course the significance level, the power, and the critical size of the shift in the population mean, are all rather arbitrary, and could be altered by small amounts without noticeably affecting the value of the test. Many subjective and economic factors enter here in practice; for example, a small critical size of the shift in the population mean could be used, without increasing the risks of error, by increasing the number of samples, but this might not be economical to do. The important thing is that sampling errors inherent in the test have been brought under control.

13. There are important cases in the engineering application of statistical inference where the power of a test need not, or

cannot, be calculated beforehand. When absolutely nothing is known about the expected dispersion of the data, and the dispersion is functionally independent of the population mean, it is not in general possible to calculate the power of a test of the population mean. Fortunately, this situation very rarely arises in an extreme form. Then again, as has been mentioned in Section 3 and will be discussed again below, it is often possible to test several hypotheses similar to the above hypothesis of "no change" at once, and in many such cases, the experimenter may feel confident that certain of the hypotheses to be treated are so outstandingly wrong (although before the data are analyzed he is not sure which ones) that they will surely be rejected even if the sample size is determined only very roughly and intuitively.

14. A particularly important case where it is not usually necessary to calculate the power is the case where a test, usually of low power, is repeated on data from a succession of samples. This situation occurs in the use of the Shewhart control chart. When the control lines for the sample have been drawn on such a chart, they set up the limits for a test of a statistical hypothesis, and this test is repeated every time a point is plotted on the chart. The test is often of low power, and the chance of falsely concluding that a change has occurred is purposely also set very low. If a change does occur, it is usually permanent enough so that sooner or later a sample point will fall outside of the control lines, and the change will be detected soon enough for practical purposes, although perhaps not immediately after it has occurred.

15. The example of the cylinders has now illustrated the fundamental elements of the inferential method of approach as outlined in Section 3 and applied in the remainder of the paper. It has demonstrated how large samples are used to make single-number estimates of key population parameters and to set up tolerances within which a given percentage of future observations should lie. It has illustrated how estimations and tests of hypotheses can be accomplished with samples of any size, small or large, by the use of statements which have a prestated chance of being true. It has brought out that for the best results, statistical investigations should be planned or designed in advance.

16. Although the example has dealt chiefly with estimation and

testing problems related to the position of a population mean, similar problems relating to the standard deviation and other parameters of the population can be handled in an almost identical fashion. All that is required is to choose the right function of the sample data and to determine its distribution by the analytical theory of probabilities.

17. The really important generalizations of the techniques so far considered occur when instead of a single population, a whole family of populations with different linearly related means is studied. This is the type of generalization which provides the statistical techniques referred to in Section 3 for experiments in which several separate causes of variation are investigated simultaneously. Such statistical techniques are involved in practically all the applications of statistical inference to research problems described in Sections 5 and 6. The remainder of this Appendix will be devoted to the discussion of these techniques.

18. To fix ideas, a special case will first be considered. Suppose that the population mean μ of a statistical variable Y (such as the volumetric capacity of the cylinders discussed above) is known to be related to a non-statistical variable x by a linear equation of the form

$$\mu = a + bx$$

where a and b are parameters which in practice would be unknown. From a sample consisting of various sets of observations corresponding respectively to a number of different given values of x, estimates of the unknown values of a, b, and the dispersion about μ of the theoretical frequency distribution are to be calculated, or hypotheses concerning the values of these parameters are to be tested, using all the data in the sample simultaneously and in the most efficient way.

19. The problem of estimation so formulated is termed a *linear* regression problem, and the equation relating μ and x is called the regression equation of Y on x. The variable x is sometimes called the *fixed variate* because the central purpose of the mathematical model is to study the random variations of Y for various fixed values of x. This model provides the standard statistical tool for measuring relationships between two variables which are

each subject to random fluctuations. In other words, this is the device used for setting up and estimating the width of the bands mentioned in the Introduction which in practice surround theorectical engineering curves. Examples of its use to fix the limits of bands and establish their central positions are illustrated in Figures 4*, 5, and 6.

20. It is customary further to assume that for each value of x the theoretical distribution of Y has the normal or gaussian form (as was done in the cylinder example) with a standard deviation which is a constant independent of x. In symbols the distribution of Y is then defined by the areas under the curve

$$z = \frac{1}{\sigma\sqrt{2\pi}} e^{\frac{-(y-a-bx)^2}{2\sigma^2}}$$

where σ is the standard deviation. (This equation should be compared with equation (1) in Section 3.) When this specification of the underlying theoretical frequency distribution is made, "best" estimates of a, b, and σ are obtained by fitting a line by the well-known method of least squares to the swarm of points obtained when the observed values Y are plotted against the corresponding values of x. The coefficients of this line and root-mean-square estimate of dispersion about the line so obtained are the functions of the sample data used to set up confidence intervals for, and tests of hypotheses concerning the values of a, b, and σ.

21. When all the values of x are taken to be equal to 0, the linear regression problem reduces from a theoretical point of view to the single-population type of situation previously considered in the case of the cylinders. When some of the values of x are taken to be 0 and some are to be taken as equal to 1, the value of b becomes merely the difference of the means of the two populations corresponding to these two values of x, as the reader who remembers his analytical geometry can easily verify. In this case, a test as to whether b is significantly different from zero is the same as testing whether the two populations have

* In the case represented in Figure 4, linearity was obtained by taking the logarithms of all the observations. The linear regression model was applied to the logarithms. Figure 4 represents the situation after the transformation back to the original scale had been effected.

different means. The practical importance of this sort of test for comparing two different materials, processes, etc., hardly needs further emphasis.

22. The most general linear regression problem is formulated in just the same way as the special one considered above, except that the population mean μ depends not on just one nonstatistical variable x, but on several. The problem is then called a multiple regression problem. For three "fixed variates" x_1, x_2, and x_3, the regression equation becomes

$$\mu = a + b_1 x_1 + b_2 x_2 + b_3 x_3$$

The reason for the great usefulness of this sort of a mathematical model in engineering research is that it provides for the systematical isolation of assignable causes of variation and the appraisal of the importance of their effects. The assignable causes are represented respectively by the fixed variates x_1, x_2, ... For example, if Y is the tensile strength of high tensile steel plate, and the variates x_1, x_2, ... are the proportions of the different chemical elements entering into the composition of the steel, and if the assumptions underlying the regression problem are presumed to hold, then when results from many heats of steel are analyzed by regression methods, the residual variation of Y about the population mean μ is free from the effect of variations in the chemical composition, and can be considered as arising only from the variation in heat treatment and in other variables of mill practice. Furthermore, it is possible by means of tests of hypotheses relating to the b's (such as the hypothesis that several of the b's are equal to zero) to decide which of the chemical elements are the really important ones in causing the tensile strength to vary from heat to heat, and which ones can be ignored, the decision being valid at least within the ranges covered by the regression assumptions.

23. As in the simpler case of the general regression problem previously considered, an especially interesting and important specialization of the general linear regression problem occurs when each x is used merely to differentiate between exactly 2 populations corresponding to 2 different treatments or materials. The mathematical model can be adjusted to this case most con-

veniently by letting some of the values of each x be equal to 0 and the rest be equal to 1. In this case, the b's reduce to differences in the various population means, and testing hypotheses concerning the b's (say the hypothesis that some of them are equal to 0) is the same as testing whether the different treatments or materials are really alike.

24. The model thus set up provides the basis for factorially designed experiments (see Section 3) in which many treatments, materials and processes are compared simultaneously and the ones which caused the main effects are singled out. The importance of such a tool for engineering research is immediately apparent. However, it is essential for the full utilization of this tool that an experiment should be properly planned or designed.

25. While technical details would be out of place here, a few words concerning the specific nature of the significance tests used in regression problems are in order. To go back for a moment to the example of the cylinders, it will be noticed that the significance test itself consisted in comparing the deviation of the observed sample mean from the hypothesized population mean with the known population standard deviation. To avoid complications at that point, it was not mentioned that in case the 1800 preliminary samples had not been available, the population standard deviation could have been estimated from the proposed new sample of observations at the same time that the significance test was performed. The test would of course have lost considerable in accuracy, but the trouble taken in making the preliminary investigation would have been saved. It is further to be remarked that in performing the test, it would have amounted to exactly the same thing if the deviation of the sample mean from hypothesized population mean had been squared and compared with the square of the standard deviation —that is, the *variance*—of the sample or population.

26. These facts are introduced here to lead up to the term *analysis of variance*, a term which occurs frequently in the modern statistical literature and which has probably aroused the curiosity of more than one engineer. In testing hypotheses concerning the means of various populations involved in a regression problem, it is usually convenient or necessary to estimate

the population variance from the sample at hand and not to use a preliminary experiment except possibly to calculate in a rough way what the power of the test is going to be. Furthermore, the most convenient test of a complex hypothesis involving several population mean values consists in calculating the sum of squared deviations of the several corresponding sample means from sample estimates of the corresponding hypothesized mean values, and comparing this sum of squares with either the known variance of the population or (more frequently) with an estimate of the population variance calculated from the sample in such a way that its accuracy is quite independent of whether or not the hypothesis to be tested is true. It is fairly evident that this is a reasonably direct generalization of the statistical test procedure used in the cylinder example. When the tests in a regression problem are properly set up, the sums of squared deviations of the sample means from their hypothesized mean values, and the sum of squared deviations entering into the variance estimate used for comparison purposes (often called the "residual" or "error" sum of squares), all add up to the sum of squared deviations of the entire sample from its overall mean—a sum of squares which would be used to estimate the variance of the experiment if no attempt had been made to remove any assignable causes. That is, the test functions of the sample data which are used are additive components of the overall variance of the sample data. For this reason, the process of calculating and setting up such statistical tests of hypotheses is called the *analysis of variance.*

27. In conclusion, as to bibliography, it is the opinion of most workers in the field that unfortunately, the testbook in engineering statistical methods has not yet been written. The facts discussed in the preceding paragraphs will be found scattered through the mathematical and biometrical literature. Therefore it is not to be expected that any one bibliographical reference will be found to be completely satisfactory. Perhaps the best source of general information on the methods of inference still lies in some of the manuals originally intended for biometricians, in spite of their omission of most of the underlying assumptions and of quantitative discussions of the power of tests.

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SCHEDULING.

By Captain James E. Hamilton, U.S.N.

Among those attributes of men, one which is almost instinctive and which is essential to an orderly life, is scheduling. Everyone, without formal plan or studied intent, schedules certain of his daily acts in order that those which must come first are accomplished before others, and in order that desired or necessary end results may be obtained.

In his personal scheduling, one, without specific definition and sometimes without consciousness of its existence, applies lead times where pertinent. Lead time is the period before some event when a previous event must occur in order that the latter may eventuate. It is the most important element in scheduling and frequently the most neglected.

A homely example of scheduling is getting to the job in the morning. The fixed requirement is that a man reach his job at a certain hour dressed and barbered appropriately. To do it successfully he must consciously or unconsciously, calculate back from the hour of arrival until he computes his rising hour. In this computation he will allow the proper amount of time for transportation, breakfast, dressing, shaving and anything else which he personally requires to prepare himself for the day.

The schedule just outlined is really a very simple part of a much more complex one. In the normal household the means for performing each of the steps from bed to job are readily at hand. Soap for the bath and shaving cream are within arm's reach. There is clean clothing ready to put on, eggs and butter in the ice box, bread and coffee in the pantry and gas or electricity standing by to be turned on. Outside is a car or a friend's car, a bus or street car ready at the right time. If one stopped to consider the number of steps and processes through which every little item which goes into making a satisfactory advent at the job passes, he would have some appreciation of the staggering amount of scheduling which it entailed. Yet when reduced

to the individual who is concerned, it seems one of the simplest of processes.

Civilization has built up a system which provides, through a multitude of informally connected schedules, for a way of living which frees each individual from all but a minute percentage of the work necessary to make his way of living possible.

A problem of a simple individual schedule has been used to introduce this subject. Example after example could be presented. However, let us proceed to the military campaign with which the United States has become so familiar during the last five years.

The campaign is part of a war. Each campaign lays the groundwork for the next one until the final war—concluding one is fought. Behind the campaign is the plan, and the plan reduces to two closely related and integrated schedules: operations and logistics. Logistics precedes operations, continues during operations, and is still continuing when the campaign has ended whether it is the last or an intermediate campaign.

A Field Commander may be told what he will have in the way of men and material, or he may be given the additional task of determining what he will need for the campaign. In either case, once the schedules are set, logistics must provide the men and material when and where required *or must advise the Field Commander of deficiencies or probable deficiencies as they develop.*

If there are no deficiencies, operations can go ahead as scheduled and success or failure is in the hands of the Commander. With adequate correct information in advance, the Commander can continuously re-estimate the situation and revise his plan, either to go ahead at the times planned without some of the elements he originally wanted or he can delay the operation until the deficiency is overcome.

The need for correct information is of vital importance if the desired end is to be attained. If, in our simple example, the man knows the night before that there will be a transportation strike in the morning he can make other plans and can reach his job in time. If in ignorance he goes blithely forth to catch his usual bus and it doesn't come, he will be late.

The subject, scheduling, is so broad that we are now going to

begin to narrow our field. We are heading for an analysis of industrial scheduling and its application to ship building and repair. As far as the Naval Commander is concerned, the end product is a collection of ships and airplane squadrons properly designed, built, manned, equipped, provisioned, and trained. For the purpose of this discussion, the manning and training are separate subjects. The scheduling of personnel must parallel that of ship construction and repair, and the two schedules must meet at a point which permits time for training before a complete unit is ready to begin operations.

It should be apparent that, from the point of view of end use of end products, schedules must all be worked backwards. Perfect logistics would always turn out that way. In every case where, in working up the schedule backward, the current date is passed, logistics take a control which is not its basic role in determining what operations can take place and when. We, in the United States, have gotten accustomed to logistic control of operations and probably believe that to be the correct philosophy. It should not be, but that is another subject which will not be discussed any further here.

Assume any condition which requires a fleet. For those who wish to think that our last war has been fought, assume a cruise around the world with the purpose of showing the flag backed by a certain amount of Naval might in certain ports. It might be that, even in a peaceful world, the Commander would require that the group entering each port would be strong enough to resist any attack. Conditions might be such that decision was reached to carry all fuel, provisions and supplies along. A good sized fleet of many types and numbers would be required. In addition, with that fleet away, it might be good insurance to have another one available in home waters. That consideration would increase the number of active ships, ready for service, which would have to be available for the operation.

Anyway, in a few words, a political decision has been made to perform a certain operation. A Commander has made a plan for the operation and has reached a decision that certain numbers of certain types of ships must be ready by a certain date. The personnel must be assembled and trained and adequate provision must be made for the consumables which the fleet will

require. Those are logistic scheduling problems beyond the scope of this article. We are concerned only with the ships and their material condition.

Providing the ships in proper condition cannot be divorced entirely from the operational plan, but this discussion can be simplified by considering that that is possible. The man who selects the ships to be used has five possibilities:

(a) Ships in commission.
(b) Ships out of commission.
(c) Merchant ships which can be converted.
(d) Ships under construction.
(e) New ships to be placed under construction.

His job is to select from the five, the force to carry out the Commander's operation plan. He has a date to meet and he has a standard of material readiness to attain. Due to conditions, let us assume that the material standard is a very high one.

Individual ships in each group, will each present its characteristic problems in addtion to those characteristic of the group as a whole. These problems will be ones of repair, alteration, or construction, and will all meet on common grounds of manufacturing facilities, labor, and material. The general problem of tying them all together will be relatively easy or difficult depending on the *time* available.

The ships in commission will vary from those which have just completed a full Naval Shipyard overhaul and are in high state of repair and have been brought to a high state of modernness by making alterations, to those which are about due for an overhaul and need repairs and lack two or more years of improvements. Ships out of commission will at least need removal of preservatives and tuning up and at most will have deteriorated and require repairs. Also, if history is any guide, their installations will be those which they had on retirement from service and they will require many alterations to make them useably modern.

Merchant ships to be converted present the worst problem. There is still some popular opinion, at times shared by people in the Navy, that this is quite simple. It rarely is. The ships may be in a high state of repair but for practically any Naval service major changes have to be made to fit the vessels for the intended

purposes and to accommodate them to the essential installations of Naval equipment.

The ships under construction will be the easiest problem if their construction has been properly scheduled. Their date of readiness for service will be known and scheduling information available will permit stepping up the construction rate, as possible, for earlier completion. If there is a requirement for new ships whose construction has not yet started, possibly whose design has not yet started, the problem from a scheduling point of view is a simple one, but the time requirements are such that the planning which developed the need for them may be thrown entirely out of gear.

Suffice it to say, if a need for ships for fulfillment of a plan should arise at any time, a scheduling problem will have been born. Exactly the same thing will be true if the need is for planes or building or automobiles. Scheduling is the heart of commercial production, but it is greatly simplified by adopting production line methods.

For successful operation of a production line, the number of units to be completed each day is the first consideration. That number will probably be decided by sales statistics and will probably be set at slightly under the market potentialities to prevent breaking the market. The sequence of assembly is the next matter to decide, then the use of sub-assemblies.

The design of the assembly facilities will determine the points at which each part enters the whole. Then all that is necessary for the material scheduler is to arrange that the number of each part required to make the line output number of completed units reaches the appointed place each day. The actual number will have to exceed those required by an experience-estimate of enough to cover spoilage and rejection. If the flow of parts is permitted to run for a few days before assembly begins, a reservoir is built up at each point to provide against excessive spoilage or supply contingencies brought about by strikes, weather, transportation break-downs, etc.

The simplicity of production line material scheduling is that it can all be controlled by a daily rate of arrival at specified points and the daily rate is, or can be, constant. Although the schedule has to be carried back to the mine or forest, responsibili-

ties can be farmed out by sub-contracting so that the force of a contract plus the power of the check to pay for performance will relieve the end product manufacturer of the need for setting up the schedule back to ultimate source.

For normal production of many end products which are not susceptible to production line methods, the United States business system provides in such a way as to reduce the end product manufacturers scheduling problem to a simple one. House building is one of these. Houses are usually assemblies of *standard* lumber, bricks, cement, plaster, hardware and plumbing and electrical fixtures. These are normally available in jobbers stocks, having been placed there by production lines. If a jobber can be found to supply, the building contractor makes his arrangements (sub-contracting) and proceeds with final assembly of one or a hundred houses. He had to schedule only from the jobber to the building lot.

The example of house building is simplified by adoption of designs which depend on *standard* components. As soon as any designer gets away from standards which are in ample supply because they are constantly used in wide-spread maintenance and repair work as well as in new end-product manufacture, he has to resort to more complete and detailed material scheduling. This is true of a new steel bridge requiring non-standard sections, of power plants, of many kinds of factories and pre-eminently of Naval vessels.

There are those who hold to the opinion that the construction of Naval vessels presents the most difficult scheduling problem of any industrial enterprise. This belief cannot be conclusively proved, but it can be very strongly substantiated. The two principal reasons for this are:

(1) The standards of design are much more rigid and

(2) A Naval vessel embodies in its make-up a portion of almost everything which enters into any and all other projects, and these are all compressed into a very limited envelope within which the relative location tolerances are very rigid.

Before proceeding beyond the introductory part of this paper, decision must be reached as to whether the remainder should be merely historical or should be based on a belief that future problems in Naval shipbuilding are going to be encountered.

A digression into a separate book is possible at this point. It would be easy to find millions of laymen who would aver that the world has seen the end of Naval shipbuilding. It would not be too difficult to find hundreds or thousands of military men who would join them with reservations.

The last war proved the usefulness of a Naval fleet in prosecuting war after practically all water borne Naval opposition had been destroyed. The United States has given history practically no opportunity to prove that a Naval fleet can prevent a war from developing. Dreamers on both sides can prove to their own satisfaction that a proper fleet is cheap peace insurance or that any fleet is wasteful and useless.

Antagonists of Navies normally wage their arguments using the last war's Navy as the basis. The proponents, on the other hand, alive to scientific and mechanical advances, base their arguments on using tomorrow's Navy for tomorrow's Naval problems.

At the moment, there is no 100 per cent modern Naval vessel, and there never will be. The lead time between conception and installation preclude such a result for Naval vessels just as it does for automobiles or radios. Therefore, as long as Navies exist, regardless of the type of ships or their individual characteristics, there will always be a material scheduling problem in order that existing ships may be kept as modern as possible and as that becomes impracticable, new modern ones take their places.

In any industrial production there are four major segments of the schedule. These are:

(a) Design.

(b) Preparation of manufacturing facilities and assembling of material.

(c) Manufacture or assembly.

(d) Test.

In some cases the four parts are distinct and separate. In building Naval vessels, they cannot be, but must overlap in order that practicable results may be attained. Because of the overlap, the schedules must be active and facile, susceptible to change and readjustment constantly. It cannot be a proposition of setting up a schedule and then leaving it to take care of itself. It won't do it, but must be nursed and nurtured continually.

As previously indicated, I want to approach this schedule in what, for most Naval construction, is an unorthodox direction. I want to assume that we have real planning and that a date in the future has been fixed on which a new ready-to-serve Naval vessel is to be delivered to the fleet. That required date of the end product is the controlling element in most production, and there is no reason why Naval planners shouldn't try the same thing.

At any rate, the reporting date is set. We now fall back on experience and decide that "A" months will be required for testing which in the case of a Naval vessel means taking its crew and outfit aboard, shaking down the crew, discovering the "bugs" and correcting the serious ones. Also using experience, which may be current or from past history, we decide that it will take "B" months from the date the keel is laid until the vessel is ready for commissioning and the start of the test period. Then from experience and a study of the current material market, we decide that it will require "C" months to order the material required at the beginning of construction and to have it delivered at or flowing to the site so that keel laying is practicable. With the design facilities available and the general type of ship, we then decide that "D" months will be required from the day the word is given to start until enough design details are available for selecting a builder, making necessary contractural arrangements and beginning to order material.

The sum of "A", "B", "C", and "D" is what the construction part of the Navy must furnish the operating part. That period is the *gestation* period of a Naval vessel and determines the date on which a "go-ahead" must be given, with legal authority and money on hand, if the finished vessel is to be ready on the date required. As a part of any peace time set up, these periods must be currently on tap and kept revised to date for all possible types of Naval vessels.

Although the design period is included in the overall period above, in an ideal set up, there would always be available a complete set of at least preliminary plans for every type of Naval vessel, constantly kept up to date, and the liaison between the operating and construction sides of the Navy should be so close

that there are always preliminary plans of all conceivable future types of special purpose vessels.

The second requirement for material scheduling is a bill of material. For a complete Naval vessel this is quite a formidable compilation. Rarely will it be found in complete form. It is properly made in sections following the development of detailed plans. Normally the entire bill of material is not reduced to the type of schedule here contemplated, but during the recent War Shipbuilding Program, it was approached.

The discussion is facilitated if we do not particularize too much at this point but consider a bill of material as being a complete list of every piece which is built into or installed in the ship, described in the form in which it enters into the ship.

A bill of material is essential to the scheduling of any job using materials whether it is the baking of a cake, the building of a ship or any greater or lesser job. It is a vital part of a ship repair or alteration job and, as I have said, is the *first* requirement after the plans for what is to be done have been drawn.

The *third* essential is the order in which the various parts are to be incorporated into the final product. This also has general application to any construction or assembly job. This order of assembly must concern the material *in the form* in which it enters the end product. It will vary between different plants doing the same job as the utilization of sub-assemblies will vary.

Whether the job is an entire new ship or work on an old one, the order of assembly must take into consideration structural strength, buoyancy, stability, and interferences. Nothing can be installed until the supporting structure has reached the point where it can support it. Before a ship is launched, assembly must have advanced to the point where a watertight envelope exists. Underwater repair work must be accomplished while the vessel is in dock or her bottom otherwise exposed. A large piece of equipment must be put in place before the surrounding structure is completed as an excluding envelope and so on.

The order of assembly is not a clerical job. It requires the best of ship building or repair knowledge and absolute knowledge and control of methods to be used and facilities to be employed Parts of it will be absolute and following materials will have to wait idle, until earlier steps of assembly are completed. Parts

of it are flexible and are originally set arbitrarily or as a matter of convenience or advantage of economy. A point often overlooked when scheduling material is that even though many elements in the order of assembly were originally flexible, as the assembly proceeds, they progressively become fixed. Even those which do not, if not accomplished when planned can accumulate to the extent that meeting the original completion date of the schedule becomes impossible.

With the bill of material arranged in order of assembly, the next step is to tie it into the calendar. Before the completion date is set, this is done by determining that each piece is to be worked into the job so-many-days before the completion date. Once the completion date is set, this easily converts into a calendar day. We then have a bill of material with each item marked with the date on which it enters into the assembly. This is an ideal *erection schedule* and it should be understood that there can and should be an erection schedule for every industrial job. *It is not restricted to ship construction.*

I have called the above an *ideal* erection schedule because it is not really of practical value except as a means of arriving at one which can be used. In the practical working of an erection schedule certain allowances should be made. These will be discussed when the erection schedule is converted into a required date schedule.

In many plants and in all of them which are true ship yards for either repair or construction certain work is performed within the plant but not on the site of the final work. In general this work consists of manufacturing, sub-assembly, or testing. Each of these requires a schedule of its own with a completion date keyed to the final erection schedule. For testing and some types of manufacture the subsidiary schedule involves only machine or hand working time and what can be termed the sub-erection schedule would merely be the working back of the completion date to the length of time required for the manufacturing or testing operation.

Where sub-assembly, that is: the incorporation of two or more parts into one part ready to install in the final assembly, is used a true sub-erection schedule is required. This gives a dated bill of material for the sub-assembly. In the ship-building (and

major ship repair) procedure in a large plant there may be sub-sub-assemblies or other preliminary ones to any degree, each of which must be separately scheduled. The net result is to establish a date on which every piece of material entering into the final job must enter the plant *in the form in which it is purchased* if the completion date is to be met by adhering strictly to the original plan of carrying out the job.

The entire plant process has had to be used in arriving at the required date for each item. Each of the schedules which has been mentioned is subsidiary to the one being aimed at, which is the *required date schedule.* Once the material enters the gates of the plant, its course thereafter can be considered as a production and not a material scheduling problem. There are still problems of handling and storing and transportation, but they are all closely under the same management which is producing the final end product and can be controlled by good management.

The working up of a complete required date schedule is rarely necessary, but alertness is necessary to know how to reduce the volume of the schedule and to know when to pick up scheduling of items which were originally considered to be readily available through other means. Many items used in ship work are normally carried, in a good plant, in stock in sufficient quantities to assure availability when needed. Others of a commercial standard nature can be purchased off the shelf on demand. If stock replenishment methods are good enough to pick up tightnesses in the market, and if dealer's stock of standard items are kept under reasonable surveillance, these types of items can be taken more or less for granted and need hardly appear in required date schedules.

In normal times real scheduling can be reduced to custom built non-standard items and this, from a shipyard's point of view, will be very few. This introduces a real danger for an organization like the Navy which can find itself entering an emergency without the framework of an organization or procedure to permit it to take emergency conditions of material supply in its stride. For that reason it would be best if complete schedules were prepared in spite of the fact that they are not necessary.

The principals of operation are identical for every item in so far as procedures are concerned. The general set up for handl-

ing all items in the bill of material are the same and not affected by whether complete schedules are made up or the minimum partial ones used.

The required date schedule establishes the date when the individual items must be received by the plant. Normally those exact dates will not be the ones specified in purchase orders for various reasons. These reasons (or some of them) can be mentioned but any analysis of them must be made on the spot to meet local conditions and current circumstances plus as much pre-vision as a practical man can allow himself to use safely. Among the principal reasons are:

(a) Insurance against unforeseen and uncontrollable delays—advance the required date.

(b) Unreliability of the source (vendor)-advance the required date.

(c) Volume buying—advance the date on later jobs for a multiple-unit job. Not applicable to a single unit job except where similar items are used at various stages in the single job.

(d) Possibility of rejection—advance the date.

(e) Restricted storage space and facilities—retard the date.

(f) Lack of credit—retard the date. This could include budgets limited by calendar periods.

(g) Possibility of change of specifications—retard the date.

(h) Tight competitive market—advance the date.

(i) Government controls—normally to retard the date.

After all of the above and any other pertinent factors are considered, the required date for each item is established as a fully practical thing. These dates control the purchase operation and would be the ones presented to prospective vendors. When the bids are received, one essential element should be the vendor's promised date and in awarding contracts or orders the effect of this date must be considered. If the date promised by the low bidder is later than the one requested, the leeway in the requested date must first be studied and then the effect of truly late delivery on the erection schedule determined. If the effect is appreciable, the *best* bidder may not be the one who offers the least price, but the one who offers the best delivery at the *best*

price. If no offer of delivery which can meet the erection schedule is received, it will be necessary at this time to revise the erection schedule to accommodate it to the promised date on the item. There may be many such items before all purchase orders are placed.

There is much thinking that all problems are solved if everything which goes into the final product is delivered well in advance of need. There are certainly many advantages in being able to draw from a local warehouse each item when it is wanted. Such a situation creates an ideal for the production department. However, the possible effects of the immobilization of material which will result is frequently overlooked.

An analysis of the problem of advance deliveries may result in the difference between profit and loss; between success and failure. Every piece of material which is stored in advance of need means:

(a) Idle investment in the cost of the item.
(b) Idle raw materials contained in the item.
(c) Idle labor production tied up in the production of the item.
(d) Investment in storage facilities.
(e) Danger of deterioration.
(f) Danger of obsolescence.
(g) Additional overhead to cover handling costs.

For a production line job, some advance deliveries are essential. There must be a pool of material at each stage in the production line sufficient to prevent stoppages due to rejection, spoilage, and to a limited extent due to delivery failures because of weather, transportation difficulties, etc.

Also in the case of repairs, pools of material are essential. Delays in effecting repairs result in immobilization of operating units whether they are radio sets, automobiles or ships. To wait for placing orders, manufacturing and delivery of replacement parts wherever repairs were required would mean an impossible tie up of operating units which could be countered effectively only by having an excessive reserve of complete, ready-to-go, replacement operating units.

However, for custom production of Naval vessels, the need for advanced deliveries cannot be justified in any excessive

amount. In normal times a combatant vessel takes many months to build and under wartime pressure the building period is still measured in months. Usually the design is progressive. Some parts are completed in the ship before the design of later parts is ready for ordering material. Also, behind the ship designers is a tremendous force of research and development engineers. To insure that the final ship is fully modern, every chance must be given by retarding the delivery and production of parts of the ship until the last acceptable moment. If this is not done, either the ship will be completed lacking in some modern feature, or real waste will be incurred in the scrapping of items delivered too soon, but not used because something better came along.

The best example of the danger of advanced deliveries could be found in the recent enormous war production. Between the needs of all of the services, there was a demand for far more raw materials, labor and production and transportation facilities than the United States contained. Overall controls were applied with magnificent, but not complete success. The controls were designed, through scheduling, to provide for delivery when needed, but not a minute earlier, each of the many war items which consumed raw materials and labor. Had the scheduling machinery been available within each agency when the problem arose, the success obtained would have been much greater. The fact which was proved to most people was that for every item delivered someplace too early, somebody else was deprived of timely delivery of some other item. This is an indisputable fact at any time when a market exists for more than the total productive capacity.

Normally, the working of the law of supply and demand provides the balance. In a wartime emergency where the Federal Government is the principal customer, controlled scheduling must be applied, and it must be realized that delivery too far in advance of need can be just as destructive as delivery too late.

Returning to our specific problem; scheduling of ship materials, we have established the scheduled bill of materials and have accommodated it as necessary to delivery promises of vendors. That part of the process is, or can be, relatively slow and deliberate. At this point, the process comes alive and its control calls for alertness. Such alertness must be alive to changes in design

and to changes in delivery. Handling the former includes the latter. The ship builder or repairer cannot sit back and assume that the delivery promised will be made. He must have machinery set up to tell him continually that it *will* be made or when and to what extent it will fail. This requires contact with the vendor and familiarity and access to the vendors schedules.

Every time advance notice is received that some item will be delayed, erection schedules can be altered or substitutes can be found before interference with production is encountered. Every time an item is needed for orderly assembly, and it is found that it was not delivered when expected, confusion results, costs will go up, and delivery dates may be missed.

This matter of following up on vendors' promises, theoretically goes back step by step to the mine or forest. As a rule, when the shipyard has made its arrangement with a vendor that is as far as it goes. It leaves to that vendor the preparation of his own schedules and the follow up of its vendors. Each of the prime vendors does the same. This is not always the case, and it definitely could not have been the case during the recent war production. Conditions which arose in general were very similar to those which *the Navy is always facing in* a much smaller way.

During the war, different agencies were competing for production in almost every production plant. During normal times, the Navy competes with itself in many plants and before the war this fact was hardly recognized. With an operating fleet and with a reasonable ship building program many manufacturers will have orders for material:

(a) From private shipbuilders for the construction of Naval vessels.

(b) From Naval Shipyards for the construction of Naval vessels.

(c) From Naval purchasing agencies for replacement parts or units for existing Naval vessels.

(d) From Naval purchasing agencies for new equipment for existing Naval vessels.

(e) From Naval purchasing agencies for stock material.

(f) From Naval or private Shipyards and manufacturers for sub-components for items being bought to ships accounts.

Sometimes these competing orders are for identical items. Sometimes they are for items which differ, but which compete within the plant for labor or production facilities. The problem which the Navy faces is to combine all of the demands into a single schedule so that the manufacturer can best meet them all.

The apparently simplest way to assemble the information for scheduling all of a plant's production which goes into ships, is to start with the manufacturer's order board. From the entire list of orders, the scheduler would select those pertaining to Naval ships, would assume that each one carried a reasonably accurate required date, and would then arrange them to give a composite picture of requirements.

The difficulty with the above approach is that many orders would not indicate clearly that they were for Naval ships; many of those which did would not show the specific Naval ships; many of those which did would not show the specific use in the Naval ships; many of them would comibne requirements for many purposes including Naval ships; and in few cases would the order show a required date of *provable* accuracy.

The approach in the other direction can yield more accurate results. In doing this, every order placed by a *Navy* activity for a ship, for service of repairing a ship, or for material for building or repairing a ship, would be recorded. Each item covered by an order, whether a complete ship or a simple part would then require a complete bill of material. Each item on each bill of material would be scheduled for a reasonable delivery date and then matched with the contractor's order for that item. Again each item on the contractor's order would be reduced to a bill of material and the items scheduled for a delivery date and matched with the sub-contractor's order and so on.

The result would be a complete set of manufacturer's order boards synthetized and showing every item which he was obligated for on account of Navy ships. If done as it should be, all of the water in dates would have been squeezed out and he could be told that failure to meet any date would, without doubt result in either a change of plans or failure to meet a completion date in some ship.

If one agency, say the Bureau of Ships, alone were to set up such thorough schedules, it would have a tremendous advantage

over other agencies competing for the same manufacturer's product. To take care of the Navy's interest, each Bureau would have to schedule all of its material and a Navy Department activity would have to combine all of the schedules in each plant. To protect the Federal Government's interest each department and office would have to do the same and a Federal Agency would have to do the combining.

If good practical schedules were to be set up as outlined above, each manufacturer could arrange his production schedule in the most practicable way to meet all requirements. Considering emergency conditions such as we have just passed through, every plant would fall into one of three categories:

(a) Scheduled orders (of whatever scope—Government, Navy, Bureau) were insufficient to require his full productive capacity.

(b) Scheduled orders were in practical balance with his capacity.

(c) Scheduled orders exceeded his productive capacity either for a limited period or over the entire scheduled period.

In the event of (a) the information disclosed by the schedule could lead to (depending on circumstances):

1. Placing of new scheduled orders where more marterial was required.
2. Diversion of orders either by transfer or by sub-contracting from plants in category (c).
3. Diversion of excess labor and materials to other plants or
4. Allocating of the excess capacity to non-scheduled purchases.

In case (b) the results would be merely close surveillance to prevent deterioration and care that no new unbalancing orders were placed. Also careful coordination between production and requirements so that artificial bottle-necks did not develop because of advance deliveries in one direction and delayed deliveries in another.

With thorough intelligent scheduling, it is honestly believed that most plants would fall into classes (a) or (b). For the relatively few which fall into (c) the necessary results would be:

1. Diversion of orders to existing facilities.

2. Conversion of existing facilities to a new type of manufacture to fill the gap after diversion of orders.
3. Expansion of or construction of new facilities, and
4. Alteration of erection schedules to best meet the deficiency without altering completion dates or rescheduling completion dates on a priority basis so that delays would be taken in those end products which the circumstances could best accept.

As has been stated, the elements of scheduling are to know *what* is wanted and *when* its delivery is required and to know well in advance when its delivery may be expected. This information can all be assembled from a table of end-product requirements, bills of material of each, erection schedules of each, and the same information for each intermediate product which finally leads to the end product.

The required information can all be assembled from papers which are practically normally available. In any usual circumstance, the details of the information are very voluminous. In times of emergency, the volume is tremendous. That fact must be recognized at the top and sufficient personnel and automatic devices must be provided. A partial scheduling job will always help but it's like trying to compress a toy ballon in two hands. As control seems to be gained, the ballon will pop out in some other spot until finally it just blows up and a completely new start must be made.

In many cases, it has been apparent that Government agencies fail to realize the scope of the job they are trying to do and because of ideas of false economy imposed at some level, try to do the job with far too few people. The final additional cost to the Treasury of these foolish attempts to arbitrarily save on overhead is incalculable but I am convinced that if the Government effectiveness could be measured by a profit and loss balance sheet, the results would be startling.

With the memories of the last National Emergency still fresh, this paper is written primarily to point out what scheduling is and what it can accomplish. The general proposition is so simple that merely to state the outline should prove the point to any intelligent reader. The United States has just seen its kind of

civilization saved for a while by the turning of its full productive capacity into channels of delivery of war material. This was done with very imperfect scheduling and much of it was just "bulled" through. Anyone connected with war production knows how fraught the experience was with poorly controlled competition between agencies and even within agencies. Not all of those people are prepared to admit that complete scheduling, centrally controlled would have eliminated a tremendously large number of headaches. That it would do so is not provable in a mathematical sense but logic seems to support that contention.

Scheduling as visualized herein would have taken much of the frenzy out of war production. It would also have had an appreciable affect on the National debt and on labor distribution problems. As a guess, and it can never be more, a dollar spent as overhead on scheduling will reduce the cost of the final job by ten dollars.

Whatever the fate of our magnificent effort for perpetual peace, there is always the possibility that the Government may be faced with a large production problem; that controls will have to be imposed to insure that the Nation's real emergency needs are taken care of before any labor effort or material are permitted to enter into less essential products. If that time comes, whether for war materials or other, and whether the war materials include Naval ships or some other currently unknown item of offense or defense, let it be hoped that the problem will be attacked with real managerial vision; that scheduling in its true sense will be required; and that the scheduling machinery is ordered by authoritative mandate and not grudgingly accepted in an arbitrarily restricted minimum by high authority. If it is, the emergency itself will occupy the center of the stage instead of being forced to the wings by a secondarily caused production emergency, and the bills may all be paid off by an earlier generation.

BEARINGS AND BEARING METALS.

By Lt. Commander Bernard O. Brouk, U.S.N.R.*

Introduction.

In this article will be discussed the types of sleeve bearings and bearing metals used in Diesel service and other types of propulsion equipment, types and causes of failure and methods of correction. The care that should be taken in the selection of the proper bearing metal for a particular installation along with the installation and operation of these bearings will be elaborated upon.

In the last four or five years during World War II, much has been learned about the behavior of metallic bearing materials. This discussion covers some of this experience by touching on such topics as effective bonding of the lining to the shell, casting technique, lining surface, mechanical properties, structure and the friction coefficient and temperature in relation to the material. A description will be given of common Diesel engine bearing operation and failures, and since there have been numerous improvements in design of the precision type bearing, the relationship of the improvements to the elimination and reduction of these failures will also be given.

Early in the war, engine designers, manufacturers, engineers, metallurgists, mechanics and maintenance men were faced with a serious problem, in that a restriction was placed on the use of tin up to only 12 per cent in the babbitt metal for "implements of war". The only exception being that existing Diesel engines, among certain other items, could use high tin content babbitt bearings provided a lead base bearing could not be satisfactorily substituted.

Bonding Problems.

To make a change-over of this kind, it is necessary to fully understand and realize that there were, in general, three types of bearing liners in operation: mechanically anchored type bear-

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ings with thick linings; chemically bonded thick linings; and new type precision bearings having thin linings, chemically and metallurgically bonded by exact methods. The bonding of the lining in the shell was one of the foremost problems encountered during war time bearing operation. The following methods of bonding were usually used: (a) shallow dovetail grooves, (b) roughened shell surfaces, (c) pointed threads and flattened and (d) undercut threads. The production methods used were turning and casting, planing and turning with a forming tool. In some cases there was a satisfactorily uniform distribution of material, and in other cases, there was not. In some instances there was a mechanical bond and in others tinning was employed. The strength of the bond was often times unsatisfactory, although a good bond was obtained by any of the above methods when extreme caution was taken in manufacture. With dovetail grooves a tendency towards cracking and separation of the lining was experienced. Often tinning was necessary even though other methods of securing the lining were used. The conduction of the heat from the bearing surface is impeded by a poor bond and may lead to failure because of uneven and excessive bearing surface temperatures. The lining will loosen quickly by fatigue cracks over poor bond areas. Often times when a bond is not sound between tin-base babbitt and bronze it can be traced to inclusions or foreign matter in the bond due to imperfect cleaning of the shell surface before applying the bonding alloy. In cases of trimetal bearings poor bond may occur between the intermediate bronze layer and steel of the shell because of non-metallic inclusions in the steel which will decrease the heat flow from the bronze to the steel and result in local overheating. It is rather difficult to detect these manufacturing defects by routine inspection, defects being usually found after the bearing fails.

Some of the bearings are extremely large, such as main and crankpin bearings on steam engines, where anchor grooves are relied upon solely to hold the babbitt metal in place. In addition to well-designed anchor grooves, tinning or some other type of bond is considered necessary. The use of a thin copper coating, obtained by applying a mixture of copper sulfate and water with a few drops of sulphuric acid added, has been recommended in

some cases to insure a bond between the bearing and the babbitt. Directional solidification should be considered, that is, the bearing metal should freeze from the bearing-back to the mandrel and not from the mandrel to the bearing. This may be controlled by an air or water spray. During pouring, churning or puddling is recommended. Improper cooling may cause segregation of component elements, such as the copper-tin or tin-antimony intermetallic compounds.

Pressure Die Cast Bearings.

Gravity cast bearings are usually metallurgically poor as compared to centrifugally cast and pressure cast. One of the advantages of the pressure die-casting method over previous methods of thin linings, is the fine structure produced by the rapid high pressure injection of the bearing metal into the cold bearing shell without any other means of cooling or quenching. The fine grain structure obtained by pressure die-casting is oftentimes superior to that obtained by centrifugal casting and contributes to an improvement in the operating behavior of the bearing metal. Lead-rich as well as tin-rich bearing alloys, can be cast equally well by the pressure die casting method since the separation and segregation phenomena observed with the centrifugal method do not occur. The fluid alloy penetrates the pores of the shell under high pressure so that satisfactory bonding is obtained either with shallow grooves, deep grooves or threads between the lining and the shell. The latter should be tinned. With the pressure die casting method the bearing alloy solidifies rapidly and uniformly at most points and permits the production of uniform linings of 2 millimeters thickness or less. The adhesion of die cast linings to the shell is extremely strong and good conductivity of heat into the shell is insured.

Centrifugal Cast Bearings and Linings.

By the centrifugal casting method, a fine grain structure, a tough layer at the shell-wall and a hardened liner surface of high strength and favorable running properties are obtained. The castings are dense and usually free from porosity. Subsequent machining is rather heavy. The fact that a shrink head or riser is unnecessary with centrifugal castings, saving in material is

accomplished. The adhesion between the lining and the shell on a lined bearing is good and the lining has good impact resistance and endurance. Particular attention and technical control should be maintained for correct heating, tinning and casting conditions so that the quality of the bearings may be assured. The surface of the shell should be machined with serrated grooves or machined to a so-called "phonograph" finish. A very fine and smooth micro-finish should be avoided and sand blasting is not recommended because particles of sand are sometimes found deeply imbedded into the metal and may not be removed by subsequent cleaning operations. The final cut should be made preferably without the use of a cutting compound because of the difficulty experienced in its subsequent removal. Wiping the machined surface with waste or any unnecessary handling should be avoided. In centrifugally casting the babbitt lining, either in an inert gas atmosphere or without it, the speed of rotation, temperature of the babbitt and rate of cooling have to be carefully controlled to reduce segregation of the copper, lead, antimony, silver, calcium or other elements to a minimum.

Successful Babbitting.

It is difficult to describe a method of static pouring suitable for all types of bearings. However, a number of suggestions can be given on successful babbitting with tin and lead-base bearing metal.

To obtain a durably tight bond, let us bear in mind that it is necessary that the bonding agent be in direct contact with the base metal. It is more difficult to bond to steel than it is to bronze due to the lack of amalgation and quick formation of iron oxide. Beneath the oxide which is easily removable, additional oxide is present which is closely united to the base metal and is not an integral part of the steel. When bonded to the oxide, the bonding agent is not adhering to the base metal but to the detached oxide, and bonding trouble, and possible bearing failure, is in the initial stages. The film of oxide will form very quickly on exposed steel surface, so quickly in fact that if the surface is brightened and allowed to stand exposed for approximately three minutes, it will possess enough oxide film, though invisible, to prevent a satisfactory bond. That film should be

dissolved and the base metal exposed directly to the tin or other bonding alloy.

In preparation of the bearing shell, all old babbitt should be chipped or melted out of the bearing and the inside of the shell scraped well with a wire brush or scraping tool. In the preparation for pouring babbitt to bronze shells, it is advisable to bore the bearing after cleaning and swab the surface to be tinned with a good commercial flux. The removal of grease, dirt and other foreign matter from the shell can be accomplished by warming it, being careful to avoid overheating. A desirable method of removing oxide film and scale and thereby produce a good clean surface, is to pickle the shells in a bath of four parts water and one part muriatic acid. In obstinate cases as for most bronze shells, the most satisfactory method of preparing a shell for tinning, is to machine or grind the surface to insure a clean metallic contact. After thoroughly cleaning, the surface should be fluxed to dissolve the oxides. One of the most satisfactory is termed "fast flux" and is easily made by mixing eleven parts of commercial grades of zinc chloride with one part granulated ammonium chloride (sal ammoniac) and then stirring boiling water into this mixture until a hydrometer reading of 52 degrees Baumé is reached. The flux is now ready for use being of good quality, easily made, and inexpensive. A flux which is old, weak or diluted, should never be used.

After the fluxing has been completed, warm the shell by plunging it into a quantity of melted 50/50 solder (50 per cent tin, 50 per cent lead) or preferably tin. A portion of the molten solder or tin will adhere to the prepared surface and can be spread over the surface with a small brush, producing a mirror-like coating. When the bearing is cooled to a temperature of approximately 250 degrees F., a bar of solder or tin, which is the bonding alloy, should be rubbed over the shell producing a "sticky" surface. A heavy coating of this bonding alloy should be applied to the shell before pouring of the babbitt. If the bearing shell is not too hot, the poured babbitt will unite and fuse with the treated surface, and a close bond will be assured.

In preparing the mandrel, it should be warmed to an approximate temperature of 250 degrees F., care should be taken not to greatly exceed this temperature. An extremely hot mandrel will

cause blistering and air pockets to form in the lining. The usual procedure is to chalk the mandrel or paint it with a mixture of clay and water, graphite or similar refractory composition to prevent sticking. However, in some instances, better results are obtained by pouring against the bare warm mandrel. The jig and assembly should be carefully checked for leaks and made as tight as possible with any good caulking clay, to prevent loss of metal during pouring.

In melting and preparing the babbitt, the melting should take place slowly. The suggested pouring temperature is 775 degrees-900 degrees F. for tin-base babbitt, and 600 degrees-650 degrees F. for lead base bearing metal. The temperature should be pyrometer tested and not tested by the use of a white pine stick. As soon as the babbitt begins to melt, the surfce should be covered with powdered charcoal. This will act as a protective covering from air, thereby materially retarding formation of oxides and accumulation of dross. When bars or ingots have been completely melted, and babbitt is in a fluid state—stir thoroughly over and over. It is recommended, if practicable, that the same person or persons do the rebabbitting, as experience enables them to secure the best results.

Be sure that the bearing and mandrel are not wet or damp, for hot metal coming in contact with moisture will splash or explode —sometimes causing painful and serious burns to personnel.

If practicable, babbitt should be melted near the location of pouring. If molten metal is carried any great distance, it will cool rapidly, and by the time it is poured—may well be in a sluggish state and thus result in a poor bond. (Tight linings insure longer bearing life—thus fewer babbitting operations and replacements). If it is impossible to pour close to the point of melting, the babbitt should be heated from 25 degrees F. to 50 degrees F. over recommended pouring temperatures to allow for cooling during transit.

The size of the ladle and quantity of metal melted is important. A ladle or ladles, sufficiently large to hold all the metal necessary to pour the entire bearing at one time, should be used. More babbitt should be available and melted than is actually required. An excess amount can always be used with the next pouring. If additional babbitt has to be secured, melted and added, after part

of lining has set, a definite seam and cold sheet is formed. This weakens the bond, causes premature loosening of linings, squashing, rapid wear, and sometimes complete failure. An improved ladle—the bottom-pour self-skimming type—prevents any dross, dirt, oxides or impurities from entering the part to be poured.

In pouring the babbitt, the metal should be thoroughly skimmed, stirred, then ladled out—dipping from below the surface—and poured slowly and steadily, in a thin stream. A quick, thick stream, which rapidly fills the lining cavity, prevents the necessary escape of air, and causes porosity or seams in the lining. A certain amount of shrinkage will take place, as the lining sets, so additional babbitt should be promptly added, during the setting process, until the lining is flush with the end of the bearing. The optimum results are usually obtained by wrapping the outside of the poured bearing with wet cloths, replacing the cloths several times. This causes the shell to clamp on to the lining and give an excellent bond.

An air pocket in the lining or between the lining and the shell is a serious defect. Being directly connected with the oil supply, the pocket as a general rule, soon fills with oil. Oil does not transmit the heat of friction as rapidly as babbitt or bronze. When the babbitt heats slightly, the oil in the pocket prevents the heat from being conducted to the shell, and the babbitt rapidly becomes hot, the babbitt lining retaining the heat instead of transmitting it to the shell. Continual running in this condition will result in melting the babbitt.

When a bearing is installed the immedite effect of the load and vibration is to cause the lining metal structure to "pack" until, by closing the voids and becoming more dense, there has been set up in it sufficient resistance to offset the forces working against it.

In preparing bearings it is necessary to handle the work so that the babbitt freezes with as solid a structure as possible. The warmer the babbitt and mandrel mold when the lining is poured, the slower the cooling of the metal. No set rule can be made for heating babbitt. Some bearings are more difficult to pour than others and for such bearings slight additional heat should be used.

Bearings that failed because they checked, cracked, crumbled or chipped out in pieces, usually have failed from one of two reasons: poor anchorage, or poor bonding. These two deficiencies

are caused by cracks which are produced by the shrinkage strains that are set up in the babbitt while it is cooling.

The higher the temperature of the babbitt when poured, the more it is expanded, and the more it will contract during cooling, and therefore, the more severe the shrinkage strains will be. The warmer the mandrel and shell the longer the babbitt will remain in the freeze range and so give more chance for the cracks to form. If the mold or mandrel is overheated, the heat will be held in the cooling babbitt longer thereby increasing the possibility of cracks. Therefore, the best way to stop the loss of linings that break from shrinkage cracks is to see that the bearings are poured while the metal, mandrel and mold are as cool as possible without producing a misrun.

Air is present in the mold and to produce a solid casting the air must be eliminated. In handling an ordinary mold, the simplest way is to start the pour slowly, so as to warm and expel the air from the mold, and then finish with a strong steady stream.

Lead Bronze Bearings.

The belief that cast lead-bronze bearings are suitable only for engines in which they are subject to high dynamic stresses is erroneous. It is believed that this type of bearing is needed today in machine tools and engines wherever static stresses are produced and generally in steam turbine construction. In this connection, the use of lead-bronze in locomotive and rolling stock construction, as well as ship propulsion equipment may be mentioned. This type of bearing may find many applications in the future. Lead bronze bearings may be satisfactorily used with similar small clearances usually adopted for white bearing metals. In precision bearings the lead-bronzes are irreplaceable as bearing metals.

It is a general hypothesis that a good structure is one containing hard crystals, which, finely divided in a softer matrix, support the shaft and about which the oil is retained. On the one hand, copper-rich bronzes, which exhibit only one type of crystal have good running properties under certain conditions, while lead-bronze, which contains few hard crystals, also constitutes a good bearing material in certain circumstances, so we may be tempted to reject this hypothesis. On the other hand there can be no

doubt that lead bronze or lead-containing alloys, which have separated out and have a non-uniform structure, are unsuitable as bearing-alloys. Tests confirm this and it is questioned how these facts can be made to agree with the theory of research-workers in problems of oil-flow who contend that the shaft is carried by the oil film alone. The importance attached to the structure is shown by the considerations of material investigators when reporting results of tests or operational experience with bearing alloys. Tests have shown that in lead-bronze containing 71-78 per cent Cu, 20-28 per cent Pb, 1-6 per cent other additions, used for bearings in internal combustion engines, fluctuations occurred in the lead content and in the structure. Even within one casting, there was lack of uniformity, since layers in the vicinity of the shell contained more lead than those at the running surface. It cannot as yet be definitely determined whether any given lead content gave special advantages; a lower lead content evenly distributed generally gave better results than more lead in an unsuitable structure.

With relation to copper-lead bearings, a test of centrifugally cast bronze-back, babbitt lined and lead-tin coated connecting rod diesel engine bearings is of current interest. The report of test covers results of approximately 1600 hours satisfactory operation in a General Motors V16-278A diesel engine and the test is being continued. The test bearings, consisted of centrifugally cast high lead bronze backs. The bore surfaces of the upper shells were gridded and the grids filled with "silver-lead-base babbitt" by centrifugal casting. The upper shells were then successfully lead and tin plated, the lead and tin coatings being allowed to fuse by immersing the shells in an oil bath at approximately 350 degrees F. The linings on the lower shells consisted of "silver-lead-base babbitt".

Another test of high-lead bearing bronze of current interest is the 70 per cent Cu, 30 per cent Pb bearing metal linings bonded on steel backs by a special process. The bearing metal is a solidified emulsion of virgin lead in electrolytic copper and bonded to a steel backing in such a manner that the bearing metal does not break loose from the steel shell. No alloying substances are added to the pure copper and lead. The bearings are not too hard, and the shaft scoring and shaft wearing ten-

dencies of alloyed copper-lead bearings is absent. The report of test covers approximately 4300 hours operation of this type of connecting rod bearing in a General Motors V16-248/278 Diesel engine. The performance of the bearings was satisfactory.

In further investigation of copper-lead alloy, bearings were tested in connecting rods of diesel engines which consisted of 76 per cent copper, 24 per cent lead plated with 0.0010 to .0015 inch of lead-base babbitt (8-12 per cent tin, remainder lead) on a steel back. These bearings differ from tri-metal bearings in that the tri-metal bearing intermediate layer consisted of 80 per cent copper, 10 per cent tin and 10 per cent lead and the cast babbitt coating was .002 inch thick and consisted of 3 per cent copper, 7 per cent antimony and 90 per cent tin. The test covers approximately 3400 hours operation in a General Motors diesel engine and the performance of the bearings was satisfactory.

Aluminum Alloy Bearings.

Corresponding with copper-lead alloys, in which soft lead globules are embedded in the copper matrix and which show good running properties, aluminum alloys have been produced in which a slightly hardened aluminum matrix contains embedded softer constituents, having a lowering melting point, such as tin or lead. Such alloys show relatively low hardness and may be used with unhardened shafts.

A test was made of aluminum alloy bearings in a Fairbanks-Morse 10 cylinder Diesel engine. These bearings were cast in permanent molds after which they were subjected to a heat treatment of aging of 8 to 12 hours at approximately 420 degrees F. with no quench. The ends of the castings were faced and pressed or cold worked, until the length of each casting was decreased 4 per cent. This cold working was to increase the tensile strength from 8500 psi. to 16,000 psi. The bearing alloy consisted of approximately 5.5-7 per cent tin, .7-1.2 per cent copper, .7-1.2 per cent nickel and remainder aluminum. It is believed that approximately 1 per cent tin forms an eutectic with the aluminum. The test covered approximately 3000 hours of operation and indicated satisfactory performance. The average wear of .0015 inch in the load areas of the main bearings and .0017 inch in the load areas of the connecting rod

bearings was indicated and is considered low. The test was also run with satisfactory results in the Baldwin, Model VO, Diesel engine.

With the use of light metals for bearings in the past, it has been observed that the same alloy behaved well in one case, but failed in another in spite of apparently similar conditions. The reasons have not been fully explained but may be concerned less with the material itself than with the faulty design in that the characteristics of the material have not been sufficiently taken into account in design. Aluminum base alloys may be used without special difficulty for the less highly stressed bearings. The shaft is attacked only in the case of the high-silicon aluminum bearing alloys. Since these latter alloys are quite hard, the brittle silicon crystals are easily broken away, and they then attack the shaft in the same way as grains of emery. Although such alloys have ceased to be used, they have caused a certain amount of misgiving concerning light-metal bearing alloys.

As mentioned above, however, some aluminum alloys have shown good running properties even in highly stressed bearings at high operational temperatures. Particular care is needed in the design of light-metal bearings, according to their use as complete, divided, or supported bearings and particular attention must be paid to the machining of the running surface, clearance and the expansion, lubricaton and thermal conditions. With proper considerations, useful light metal bearings may be produced for many purposes.

An aluminum-lead-antimony alloy, containing additions of copper, manganese, and iron, exhibits high capacity for deformation. Thus the resistance to repeated impact, such as is produced in internal combustion engines, is very high so that crumbling of the lining, such as is sometimes observed with white metals does not occur. These softer alloys with Brinell hardness between 30 and 50 are intended to replace the white metals and they may be cast, pressed or rolled. They are classed, therefore, between the soft and the hard bearings alloys. Whereas the harder light-metal alloys may be substituted for bronzes with some advantage; softer light metal alloys are recommended. These have a very high capacity for upsetting. They are, therefore, only slightly sensitive to edge pressures; the hard alloys on the

other hand show great resistance to permanent deformation. The latter alloys are suitable only for very highly stressed bearings where no edge pressures are produced and where importance is attached to high resistance to upsetting at high temperatures, such as in force-fit bearing bushings.

The behavior of a bearing material is measured by certain criteria, apart from all the properties above mentioned such as the running characteristics which are expressed by the friction coefficient and a satisfactory bearing temperature. There are many influences, apart from the material, which affect the results such as: good running properties under high loads or at high velocity; good strength, particularly at high temperatures; high melting point; low sensitivity to irregularities in the drive, little wear on the shaft or bearing; low oil consumption, small clearance; simple bearing operation; possibility of machining to fit to facilitate production and spare-part delivery and lowest possible weight.

Bearing metal literature contains numerous examples of friction coefficients and temperature measurements on many bearing materials, as well as design recommendations and examples of practical application. In the design of bearings for internal combustion engines, the crankcase and shaft should be so constructed that the bearings are uniformly stressed and the entire running surface of the individual bearings is used, as far as possible, to absorb the forces. Failure is usually attributed to the fact that only a section of the surface provides support and that section is then overloaded.

Running Surface Conditions.

As a comparative standard for the evaluation of the running qualities of various bearing metals, the variations which the running surfaces undergo under simulated operational conditions in the testing-machine, may be used. The changes taking place at the running-surface during running-in govern the behavior in the engine. A mirror-like finish is formed at the points on the surface which, owing to the unavoidable deviations from the ideal cylindrical shape, are the first to absorb the total bearing pressure. With ordinary white bearing metals, this process lasts for only a few hours, owing to the low resistance to deformation,

whereas with the lead bronzes, it may take 30 to 40 hours. However, the inoculation of tin base lead-free babbitt with metallic nickel of approximately .10-.50 per cent forms a mirror-like finish and maintains it and thereby extends the life of the bearing lining. After the extent of this period, materials with insufficient endurance show signs of the characteristic crumbling, to a greater or lesser extent.

At loads, the magnitude and direction of which remain constant, white metal bearings of overhead countershafts, for instance, attain a life of some years. The permanently smooth bearing surface assists in the realization of pure fluid lubrication so that wearing of the surface is very slight.

In internal combustion engines, however, the bearings are not generally ruined by surface wear. The rapid variation of the bearing-pressure, both in magnitude and direction, produces fatigue stresses which tend to disintegration of the structure. The hairline cracks, which appear at first, can be recognized by the escape of the oil forced into them by the pressure of the oil-film. It is often possible, when examining bearing linings, to detach small pieces. The underlying surface is almost always found to be covered with oil which has been forced in. Thus the lining has already been separated from the shell during operation. In practice, this phenomenon has frequently led to the assumption that bonding "failure" has occurred.

Lead-bronze bearings develop a dark surface color, apparently due to oxidation of the copper in the matrix. The formation of a running surface in these bearings, begins with the detachment of the superficial lead inclusions from the matrix. Between these two there is only a weak mechanical connection in that the lead particles are surrounded. In operation, the upper part of the envelope is cut away and the lead is freed. The locally produced excessive loads cause the lead particles to melt while the matrix is deformed plastically. According to investigations, a film is said to be formed over the surface, consisting of compounds of the constituents of the oil and the metals. These are said to account for the gloss apparent on lead-bronze bearings immediately after operation. Under the influence of fatty acids, lead soaps may be found, and this favors the separation of the free lead. This latter may also act as a lubricant and may fill in

irregularities in the running surface. Wearing of the matrix is attributed to mechanical abrasion. In this case, the effect of the lubricant is the same as that of a cutting oil in any machining operation.

The hydrodynamic lubrication theory provides a sufficiently exact estimation of the essential dimensions such as pressure and clearance for average velocities and loads. The necessary increases in loads and velocities, however, cause such a reduction in the minimum clearance that the surface forces are effective at the shafts, the lining and in the oil, so that the bearing operates within the boundary friction range, which has not been extensively investigated. Here, the influence of the material is most important. It is known in practice that the different bearing materials exhibit varying load carrying capacities; practically no investigations have been made to indicate the physical reasons for this.

Designers should not estimate the possibility of using a new bearing material on the basis of the "running properties" and other technological characteristics such as static and dynamic strengths, wear resistance, friction coefficient and thermal conductivity alone but should base the decision on practical tests in a bearing test machine and in the actual equipment for which it is intended.

Bearing Failure Survey.

In order to intelligently determine and apply preventive measures to reduce the number of bearing failures, the Navy has investigated and made a survey to determine the most prevalent causes of failures in types of machinery, installations and bearings where failures have occurred the last four years. In interpreting the survey, attention is invited to the following:

(a) These failures are not a complete total of all of the failures during the survey period.

(b) The assignment of causes has necessarily followed the interpretation of the commanding officer of the vessels concerned.

The causes of failure were classified as follows: conditions of operation, bearing metal, foreign matter, lubricating system, align-

ment of parts, indefinite causes, design, failure of other parts, and lubricating oil.

The causes, "bearing metal", "design", "lubricating oil", and "indefinite" are all subject to personal interpretation and might be questioned technically or all classed as "indefinite". For example, before a failure could be definitely classed as "bearing metal", "lubricating oil" and to a lesser extent "design", a careful laboratory examination might be required. Failures due to "foreign matter" such as water, sludge, or particles of metal in the bearing, broken parts in the "lubricating system", "misalignment of parts", and "failure of other parts" could be readily recognized aboard ship. Failures due to improper installation, repairs, operation or inspection are subject to circumstances.

Approximately four hundred seventy (470) cases of bearing failure were reported in the survey. One hundred twenty six (126) and one hundred fourteen (114) were attributed to "operation" and "bearing metal" respectively, accounting for 50 per cent of the cases. The significance of "bearing metal" as a general cause is reduced in that eighty (80) cases out of one hundred fourteen (114) occurred in diesel engines. Thus "operation" remains as the prevalent general cause of failure for all machinery types other than diesel engines.

The one hundred twenty-six (126) cases ascribed to "operation" may be further broken down as follows: improper operation, 43; improper installation, 37; improper inspection, 27; miscellaneous, 12; and improper repairs, 7. Of the above, 60 cases of operation and inspection may be attributed to ships force and 44 cases of installation and repair to other than ships force.

Relative to ship types, "operation" failures are approximately equally divided between submarines (35), surface combat vessels (48), and auxiliary vessels (43). Relative to type of failure "operation" failures resulted in primarily "wiping or burning" (67) and "overheating" (46).

Bonding Tests.

Tests were conducted to determine the bond strength or resistance to shear of babbitt linings on steel shells. The assembly furnished for test consisted of a steel half-shell 5¾ inches diameter by 5 inches long containing a tin base babbitt lining about 7/16

inch thick. The inside surface of the shell was full threaded with 12 threads per inch as a means for anchoring the babbitt. It is understood that the shell was formed from plate stock. The normal method of construction of reduction pinion bearings employs dovetail anchors and for a comparison a bearing shell of dovetail construction was prepared, and an assembly consisting of one steel half-shell with dove tails and the other plain bearing was cast with Navy Grade 2 babbitt.

In previous tests the bond strength was determined by pushing rings or half-rings of bearing metal from the backs. On account of the threaded surface of the half-shell, it was considered desirable to perform such tests parallel with the threads as well as transverse wth the threads. The procedure of pushing rings from the backs as done heretofore is not well adapted for the circumferential direction. Consequently the linings of the bearing half-shells were segmented so as to provide regularly distributed 1-inch square blocks of babbitt. These units were tested individually and the over-all bond strength or resistance to shear evaluated on this basis.

The single shear strength of the babbitt as determined with a .250 inch diameter specimen in a double shear block was 8350 psi. The tests have shown that the bond strength provided by casting the bearing metal against a threaded steel back is fully as good as when casting is done against a steel back containing the conventional dovetail grooves. In fact, the former construction provides greater resistance against the lining turning in the shell.

In comparison of the quality of sprayed babbitt with poured babbitt, a test was conducted on two half sections of 8-inch diameter steel bearing shells, 6 inches long. A circumferential band three inches wide at the center of the shells contained a deposit of sprayed babbitt, .030 inch thick. The steel surface had been grooved and knurled preparatory to spraying. The babbitt was applied to the outside surface of the bearing half-shells in order to simulate conditions in a connecting rod which may contain an external pad of babbitt metal as a wearing surface. It is impractical to apply this pad by the usual hot pouring processes as the connecting rod at this stage of fabrication contains a copper-lead alloy bearing. The quality of the bond as well as

other physical features indicate that the sprayed babbitt should perform satisfactorily. Whether or not sprayed babbitt will perform satisfactorily as bearings for rotating members has not been established as a result of these tests.

Supersonic Method of Testing Bearings.

A non-destructive method was developed of detecting the presence of air bubbles between the lining and the steel body of the bearing—a problem that has received considerable attention in this country. The method developed takes advantage of the well-known fact that sound cannot be efficiently transmitted through a lamina separating two similar media if the acoustic impedance of the material in the lamina is quite different from that of the other two media and if the thickness of the lamina is large compared to a wave length. The first condition is easily satisfied since the acoustic impedance of air is approximately 1/100,000 that of the surrounding metals. The second condition is realized by employing a high frequency sound beam (10 megacycles per second). Under these conditions it is claimed that air bubbles having thicknesses as small as .1 millimeter could be detected. The testing procedure has been reduced to the simple operation of placing the bearing to be tested in a jig and rotating it slowly while noting the indications on a meter. A sudden drop in the meter indication signifies the presence of an air bubble. The whole operation can be completed in a few seconds. The apparatus is easy to construct and simple in its conception and operation. The test routine is simple and rapid. Consistent results can be expected if precautions are taken to remove extraneous air bubbles from the system. It is not believed, however, that the sensitivity of the device is sufficient to insure an adequate bond between the bearing and its lining. Air bubbles tend to be elliptical in shape and even if the bubble is only .1 mm thick (.004 inch), it still may cover a considerable area. Such air bubbles are serious both from the standpoint of failure under the application of repeated stresses and from poor heat conduction. The method does appear, however, to have merit as a preliminary test procedure and, as such, may be of interest to the bearing industry.

Surfacing and Finishing Shafting of Bearing Surfaces.

The frictional characteristics of several types of sprayed steel bearing surfaces were determined by operating metal sprayed spindles in a bearing testing machine. The surfaces of the steel spindles were prepared by shot blasting or fuse bonding and sprayed with steel of 13 per cent C., .25 per cent C., 10 per cent C., .40 per cent C., and .80 per cent C. The bearing surfaces of the spindles were 6.25 inches long by 3.9 inches in diameter and were finished by grinding. The thickness of the sprayed metal was .030 inch.

The results of wiping tests on Navy Grade 2 babbitt and copper-lead bearings have demonstrated in most instances that sprayed steel bearing surfaces operate longer than hardened steel surfaces after the lubricating oil supply has been stopped. It is believed that the superior wiping properties are the result of the retention of sufficient oil in the pores of the sprayed coatings to allow for the additional period of operation. The significance of this additional time before wiping is not known, although it is probable that the extra margin of safety may be of practical importance.

Grid Bearings.

Several model tests were made on copper grid bearings on a steel backing in the Continental C-115 engine, which is a six cylinder horizontal-opposed 115 Hp. air cooled engine. The connecting rod bearings operate at approximately 3500 psi. and 2400 Rpm. against an oil hardened steel shaft with a hardness of 275-300 Brinell. These bearings were later approved for production engines.

The original bearings at the start of World War II in the Wright R-975 Tank Engine were primarily copper-lead on steel backing. It was found that particularly the rear main and the master rod bearings were severely scored by dirt and grit after only short periods in tank engines. The design of these bearings was changed to silver grid with good results. These bearings operate at reasonably high bearing loads (approximately 3000 psi) and at a maximum speed of 2400 Rpm. against an oil hardened steel shaft.

A number of tests have been run on silver and copper grid master rod bearings and it has been found that both copper and silver grid bearings will carry a maximum load which is approximately 80 per cent of that of the silver master rod bearing with a lead-indium overlay. This load is approximately 7000 psi at 3600 Rpm.

Tin Substitute Bearing Metal.

The copper base alloy containing approximately 8 per cent nickel, 10 per cent lead, 2 per cent tin and 10 per cent antimony would appear to be a promising substitute for the 80 per cent copper, 10 per cent tin, 10 per cent lead bearing bronze when used in the sand cast condition. The nickel antimony bronze has excellent wearing qualities and compressive and yield strength, but lower ductility. In applications of design for lower bearing pressures, the tin can be omitted from the nickel-antimony-bronze and an alloy obtained that has high wear resistance, but the yield point is reduced approximately 30 per cent. The wear resistance of the nickel-antimony-lead bronzes investigated was related to the microstructure. Highest properties were obtained with lead in random dispersion and the presence of antimony containing compound. Intergranular lead films caused high wear rate. In producing the alloy, excessive melting temperatures should be avoided and castings should be made in green sand or bonded core sand. Chill-cast sections of the alloy had less wear resistance than others.

Corrosion of Bearing Alloys.

The corrosion resistance of a bearing material is not its resistance to any reagent which can be found in a laboratory but rather its ability to withstand the corrosive effect of acids generated by lubricating oils. It is the resistance of bearing materials to the acidity developed by oxidation of highly refined mineral oil under normal conditions. This condition of acidity may cause pitting of bearing surfaces with consequent weakening and eventual failure.

Under present day operating conditions, tin base bearing alloys are the least susceptible to corrosive attack, and for all practical purposes, they may be considered to be corrosion-resistant.

Arsenic-hardened alloys and regular lead-base alloys are somewhat resistant to corrosion but not quite to the same extent as the tin-base alloys. The cadmium-silver, cadium-nickel, copper-lead and calcium-lead alloys are more subject to oil corrosion than the above mentioned alloys but can be used successfully however, if oil and bearing temperatures are kept low and if certain definite types of oils are used. The corroded bearing often has a pitted surface which indicates a local attack by the corroding agent. One of the basic reasons for bearing failure is fatigue which is the product of high local oil film pressure and high local bending stresses. There are of course, other factors besides metallurgical that affect the life of the bearing alloys.

A test was conducted on corrosion of bearings coated with Grade I Tectyl No. 506 Rust Preventive Compound exposed to weather. The test was performed on calcium-lead base babbitt metal, copper-lead, 70 per cent Cu, 30 per cent Pb, cadmium-silver, similar to SAE #180, and F-23, arsenic hardened lead-base babbitt. The changes in the weights of the bearings were as follows:

Bearing	*Coated*	*Uncoated*
Ca-Pb	11.5 mgs.	132.0 mgs.
Cu-Pb	11.8 "	106.6 "
Cd-Ag	-0.3 "	124.0 "
F-23	-1.5 "	11.2 "

(-) denotes loss in weight

Most of the weight increase is attributed to rusting of the steel backs. Visual examination revealed that the surfaces of the coated bearings were bright and untarnished while those of the uncoated bearings were dull and appeared to contain deposits. Photomicrographs of cross-sections disclosed no appreciable difference in the coated and uncoated bearings except in the case of the copper-lead bearings. The uncoated copper-lead lining appeared to be covered by a relatively thick irregular deposit. The lining of the coated cadmium silver bearing was considerably thinner than that of the uncoated bearing and the microstructure appears to be compressed. This was probably a result of broaching during manufacture and cannot be attributed to

the test. In the conclusions of the test, it should be noted that Tectyl No. 506, Grade 1, did not react chemically with any of the four bearing materials used in the test. The coating effectively protected the four bearing surfaces from attack by the moisture, sulphur gases, etc., contained in the atmosphere to which they were exposed.

Special Treated Babbitt Metals.

Tests of three specially treated babbitt graphitized bearings were made in a Work Factor Machine. A successful break-in run could not be completed on the first two bearings due to severe wiping at 625 Rpm. and the minimum possible lead, i.e., the combined weight only of the bearing cap, calibrated springs and journal, totalling approximately 93 pounds or 4.25 psi. The bearings were thoroughly lubricated before each test. The third bearing was run-in with pressure lubrication for 24 hours at 2650 Rpm. and minimum load as above, followed by operation with pressure lubrication for 48 hours at 2600 Rpm. and a bearing load of 150 psi. Performance with pressure lubrication was satisfactory, but when the operating conditions were changed to 660 Rpm. and minimum load as above and the pressure lubrication cut off, the bearing wiped after only 1½ hours operation. These tests also revealed poor bonding of the babbitt to the steel backs which resulted in their separation, cracking of the babbitt, and actual flow of the bonding material. It is not believed that poor bonding caused the wiping since wiping occurred at both well bonded and poorly bonded areas. Chemical and microscopic analyses of the cast alloy indicated that its composition conformed to that of Navy Grade No. 2 babbitt.

Silicone Polymer as a Lubricant.

This investigation covered seven bearing metals used with a dimethyl silicone polymer fluid as lubricant. Its principal purpose was to ascertain the lubricating value of these unusual fluids and their limitations and advantages for Naval application.

The tests were conducted in a specially developed unilaterally loaded journal bearing machine. Careful break-in procedures were used. Chromium plated high carbon steel shafts were used in conjunction with bearings of high-lead bronze, high-tin bronze, commercial brass, aluminum alloy (17S), copper, copper-lead and

Alfin metal. All of these bearings performed satisfactorily when used with the silicone fluid. Once the bearings were broken in, the silicone fluid was found to be at least equal to petroleum oils as a lubricant. The broken-in silicone lubricated bearings carried the maximum load of the bearing machine (6000 psi of projected area).

It was found that an organic silicon-containing film was formed during the long, slow break-in process. The ease of formation of this film or lacquer depended upon the bearing metal and the temperature. Such film formation on the bearing was found essential to carrying high unit loads. The need for such a long break-in could be eliminated by the application of a technique of pretreating or lacquering the bearings with silicone oil before assembling the test machine. It was also discovered that pretreated bearings were able to carry higher than normal loads when operated in contact with petroleum lubricating oil.

Maintenance and Safeguard to Operations.

Careful attention should be given to bearing temperatures at all times, keeping in mind that a temperature rise is to be expected until a stable condition is reached which may be called the running heat of a bearing. The personnel in charge of maintenance and operation of the bearings should determine the running temperature of all bearings at various speeds and loads. This may or may not be the same for all bearings of a particular unit. It should be borne in mind by operating personnel that the feature to guard against is not necessarily a high running temperature of a bearing, but a rapid rise in temperature, and an increase over the usual operating temperature of the bearing.

The lubrication systems provided are generally adequate for the purpose for which they are installed but must be given careful attention to insure satisfactory bearing performance. Most of the difficulties encountered are due to neglect of bearing surfaces or clearances, or to dirty lubricants or obstruction in the piping or other passages for the lubricant.

If the temperature of a bearing increases above its normal running temperature, the quality and quantity of the lubricant supplied to that bearing should be checked first. The supply should be increased by opening a needle valve, if a needle valve is provided, or by increasing the delivery of the oil pumps, where

practicable. The lubricant should be further cooled by increasing the flow of circulating water to the coolers.

If these measures are not effective, the speed of the unit should be reduced or the unit should be stopped. Spraying water on a bearing should not be resorted to except in a case of emergency.

Generally hot bearings may be traced to one of the following causes.

(1) Improper or insufficient lubrication
(2) Grit or dirt in the lubricant
(3) Bearings out of line
(4) Bearings improperly fitted
(5) Poor condition of bearing or journal surface
(6) Obstruction in the oil lines

If the trouble is due to improper or insufficient lubrication and is discovered before the metal has wiped, an abundant supply of lubricant should gradually bring the bearing back to its normal operating temperature. Should the trouble be caused by grit or dirt in the bearing, an increased supply of lubricant may flush out the impurities sufficiently to permit continued operation. If the trouble is caused by foreign matter in the lubricant, the lubricant will have to be renovated or renewed.

If the bearings are out of line, improperly fitted, or bearings and journals are not in proper condition, only temporary relief can be looked for by use of the various means suggested above. The most effective treatment will probably be operation of the machinery at low or moderate powers until such time as the proper adjustments or repairs can be effected.

Usually abnormal temperatures in bearings can be lowered by slowing down the unit and thus decreasing the amount of work thrown on bearings. If the trouble has reached an advanced state, it may be necessary to stop operation.

Once a bearing has wiped, it should be re-conditioned at the first opportunity. If it has wiped but slightly, it can probably be scraped to a good surface and restored to service. If badly wiped or burned out, the bearing will require replacement.

SILICONES PROMISE ADVANTAGES FOR INSULATION OF ELECTRICAL APPARATUS IN MARINE SERVICE.

By G. L. Moses.*

The advent of silicone compounds has promised much in the way of increased thermal endurance and improved moisture resistance of electrical insulation. Both of these properties are of especial interest to Naval Engineers. It therefore seems timely to review this development in relation to the application of silicones to electrical apparatus on shipboard.

Early development work on silicones dates back to 1861. However, work was initiated in this country in the 1930's by Dr. E. C. Sullivan of Corning Glass Works (Dr. Sullivan is also known as "the father of Pyrex"). In the 1930's Dr. J. F. Hyde synthesized the first flexible, thermosetting silicone resin polymer. The development progressed rapidly to the point that silicone materials were produced for special purposes early in the war.

Silicones are a new class of organo-silicon compounds built on a skeleton of silicon-to-oxygen linkages in a long chain structure. This forms an inorganic "back-bone" for the silicone molecule. To this are attached hydro-carbon radicals which are derived from organic compounds. This differs essentially from comparable organic compounds in that the "back-bone" of most such organic molecules is a carbon-to-carbon linkage. The silicon-to-oxygen bond of the silicone compounds is stronger and more heat stable than the carbon-to-carbon bond of the organic hydrocarbon compounds. In one sense, it may be said that silicones bridge the gap between organic materials such as cotton, silk, wood, petroleum and rubber on the one hand and the pure inorganic materials such as asbestos, mica, sand, quartz and glass on the other.

It can be said that silicones are derived from sand, brine, coal and oil as ultimate source materials. However, as in the case of

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certain of the organic high polymers described as coming from coal, air and water, their synthesis involves a number of steps and a considerable amount of industrial and chemical technology. As indicated in Figure 1, sand provides the source of silicon and when heated with coke from coal and chlorine from brine, forms silicon tetrachloride. Organic chlorides, made from hydro-carbons derived from coal and oil by treatment with chlorine from brine are attached to silicon through the use of magnesium metal also from brine. This reaction replaces one or more chlorine atoms in silicon tetrachloride with a hydro-carbon radical as shown in the illustration, to produce a variety of organo-silicon chlorides. These are then treated with water to remove all the chlorine and by-produce magnesium chloride. The silanols thus formed condense with each other to build up long chain molecules in a manner similar to the hardening of a silicic acid gel or the setting of a phenol-formaldehyde resin.

One of the first types of silicone polymers to reach commercial production was the liquid silicones. Several groups of these silicone fluids are now available in a wide range of viscosities. They have interesting properties of low change of viscosity with temperature, low freezing point, unusual chemical inertness and stability to heat. The silicone fluids are finding application as gauge liquids, damping fluids, and in various hydraulic applications. A significant application is the use of a dilute solution of silicone fluid for treating ceramic surfaces to render them water-repellent. Another interesting use of silicone oils is as an anti-foaming agent. It was found that a few parts per million of silicone fluid in diesel lubricating oil inhibits foaming more efficiently than any other material ever found. This silicone treated oil was used exclusively for submarine and aircraft during the war.

Silicone products may be used in the vapor state to render various conventional materials water repellent. Even a piece of common blotting paper may be treated so that it sheds water and may be said to be "ink-proof" or "water-proof". Similarly various types of textiles and papers may be "water-proofed". Such treatment is successfully applied to glass and ceramic insulators which may operate under high humidity conditions.

One group of silicone fluids is for use down to -55° C. and

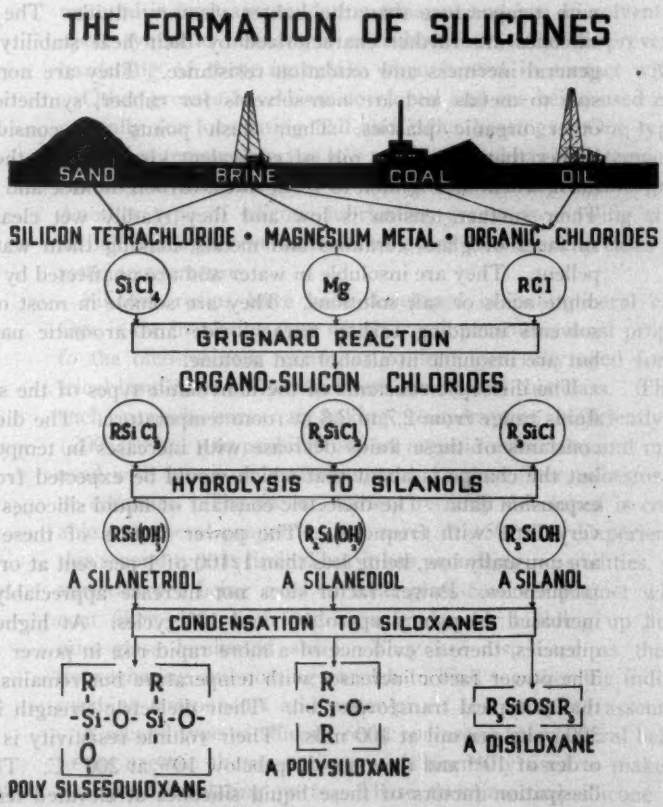

THE FORMATION OF SILICONES
SAND
BRINE
COAL
OIL
SILICON TETRACHLORIDE • MAGNESIUM METAL • ORGANIC CHLORIDES
SiCl4
Mg
RCl
GRIGNARD REACTION
ORGANO-SILICON CHLORIDES
RSiCl3
R2SiCl2
R3SiCl
HYDROLYSIS TO SILANOLS
RSi(OH)3
R2Si(OH)2
R3SiOH
A SILANETRIOL
A SILANEDIOL
A SILANOL
CONDENSATION TO SILOXANES
A POLY SILSESQUIOXANE
A POLYSILOXANE
A DISILOXANE
SIMPLE TYPES OF STRUCTURAL UNITS PRESENT IN SILICONES

FIGURE 1

below. The viscosity grades above 20 centistokes are nonvolatile and useful as liquid dielectrics. Their temperature coefficient of viscosity is very low. Higher viscosity types are nonvolatile liquid dielectrics with an even lower rate of viscosity change with temperature than the lighter viscosity fluids. The liquid silicones are further characterized by their heat stability, their general inertness and oxidation resistance. They are noncorrosive to metals and are non-solvents for rubber, synthetics and other organic plastics. Their flash points are considerably higher than petroleum oils of equivalent viscosity and they will burn, when once ignited to form silica, carbon dioxide and water. Their surface tension is low and they readily wet clean, dry surfaces of glass, ceramics and metals, making them water repellent. They are insoluble in water and are unaffected by water, dilute acids or salt solutions. They are soluble in most organic solvents including carbon tetrachloride and aromatic naphthas but are insoluble in alcohol and acetone.

The dielectric constants of the nonvolatile types of the silicone fluids range from 2.7 to 2.8 at room temperature. The dielectric constants of these fluids decrease with increases in temperature but the change is about that which would be expected from the expansion data. The dielectric constant of liquid silicones varies very little with frequency. The power factors of these fluids are unusually low, being less than 1/100 of 1 per cent at ordinary frequencies. Power factor does not increase appreciably with increased frequency up to 10^7 and 10^8 cycles. At higher frequencies, there is evidence of a more rapid rise in power factor. The power factor increases with temperature but remains lower than a typical transformer oil. Their dielectric strength is 250-300 volts per mil at 100 mils. Their volume resistivity is in the order of 10^{14} and does not drop below 10^{12} at 200° C. The low dissipation factors of these liquid silicones at elevated temperatures or at high frequencies and their inertness to moisture indicate them for use in liquid filled condensers.

A translucent silicone grease of vaseline-like consistency has been developed for use as a lubricant for ignition cables, to reduce corona cutting of the insulation and permit easy wiring of igniton harnesses. This silicone grease made an important contribution to the success of military aircraft during a critical

stage of the war. This compound is stable to heat and retains its vaseline-like consistency from -40 to 200° C. Although it is a soft grease in appearance, it has the unusual property of not melting on exposure to heat, and has no liquid phase. This material is inert and oxidation resistant and has no solvent effect upon synthetic insulations or rubber but tends to prevent the hardening of these materials when heated in contact with air.

Other greases have been developed and are being used experimentally for lubricating ball and roller bearings. One type can be used at temperatures as low as -60° F and has high temperature stability at least as good as the best available organic greases. Another type of silicone lubricating grease is showing stability in ball bearings several times as great as organic greases at the same temperature.

Silicone resins have been developed in two general classes. One is the insulating type which is comparable in most properties to the oleo-resinous varnishes so long generally used for electrical insulation. There are two varieties of this class. The first such varnish cures at baking temperatures sufficiently high (200-250° C.) to prohibit use on organic materials, and must be used with inorganic materials, such as glass fiber, asbestos, mica or ceramics. The second variety recently developed is comparable in general properties but cures at 150° C. Experience on this second type is limited but it has promising possibilities. Both varieties are being used to treat glass-covered magnet wire, to coat fiber glass cloth and as a binder for building up flexible-mica-glass laminated sheet. They are also used as the final impregnating and coating varnish to bind together the individual machine components and water-proof the complete assembly.

A second type of silicone resin corresponds in general behavior to the organic thermosetting resins normally used to make rigid laminated insulating parts. These thermosetting silicone resins are being used to bond fibrous glass and asbestos laminated structures, and to bond special coils requiring hardness and rigidity.

The well publicized but useless "Bouncing Putty" was the fore runner of silicone rubber which is now called Silastic. These silicone rubber compounds are a useful addition to the insulating materials, especially for high temperature applications. They withstand both low and high temperatures without damage.

While the initial batches of Silastic had relatively low tensile strength and tear resistance, recent major improvements have been made in these properties. It is available in forms suitable for compression molding or extruding in a considerable range of hardnesses. It is also made as a paste dispersed in a solvent for coating purposes. This heat resistant rubber-like material is being used as covering on wire and cable as well as resilient tubing and gaskets for high temperature uses. It is frequently used in combination with Fiberglas cloth reinforcement.

Before adopting silicone materials for use as electrical insulation, the electrical industry first subjected the basic materials to laboratory tests such as used for testing organic varnishes and bonds. The most common test is for flexing life on metal panels. This test corresponds to the ASTM "heat endurance" test for varnishes except that tests are made at temperature of 250° C. instead of 110° C. as used for organic varnishes. For these tests, a film of .002 inch thick is coated on each side of an aluminum panel .005 inch thick. After aging at temperature, the end-point is determined by bending the panel around a ⅛ inch diameter mandrel. Time at temperature, when breakage of the film occurs, is considered the "life" of the varnish by this test. The results of a series of flexing life tests for a silicone resin and one of the better organic synthetic resin (phenolic-alkyd) varnishes are shown in Figure 2. This includes flex life determinations made over a wide range of temperatures. These tests clearly indicate the different order of magnitude of the thermal endurance of the silicone varnish. It is of particular interest to note the tests indicate that the silicone varnish life follows the form of the law generally accepted for insulation life, as the value is reduced by one-half for each 10° C. increase in temperature.

Numerous other tests of materials showed similar advantage in the thermal aging of silicone varnish over the best organic materials. Tests on sample a-c stator coils also show results comparable to those on materials and varnish films. A typical series of tests compares standard Class B stator coils and similar silicone insulated coils which are identical in all respects except for the bonding resins, impregnating varnish and surface film. The coils use glass insulated wire, glass-backed mica wrapper on the slot section, glass-backed mica tape on the diamonds, and are

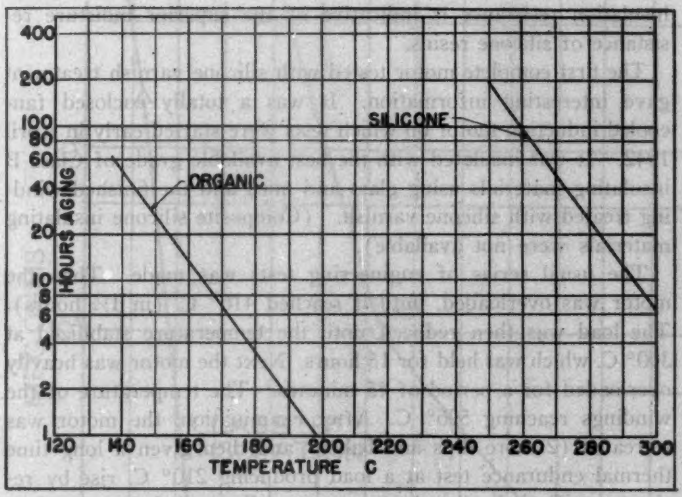

400
200
100
80
60
40
20
10
8
6
4
2
1
HOURS AGING
SILICONE
ORGANIC
120
140
160
180
200
220
240
260
280
300
TEMPERATURE C

FIGURE 2

taped all over with glass tape. In the series of tests, the moisture resistance of the two groups of coils is compared in Figure 3 during aging at 200° C. in air. The initial resistance as well as the values after aging were determined with the coils half immersed in tap water. The values were all measured with a 500-volt d-c megohm bridge one minute after voltage application after one hour in water. The curve clearly indicates the considerable improvement obtained in thermal endurance of the moisture resistance through the substitution of silicone resins for high-grade phenolic-alkyd resins. The difference in the initial insulation resistance is indicative of the superior moisture resistance of silicone resins.

The first complete motor tested with silicone varnish treatment gave interesting information. It was a totally enclosed fan-cooled induction motor on which tests were started early in April 1942. It was insulated with the best available grade of Class B insulating materials using glass and mica and the finished winding treated with silicone varnish. (Composite silicone insulating materials were not available).

The usual series of engineering tests was made. Then the motor was overloaded, until it reached 416° C. (in 1½ hours). The load was then reduced until the temperature stabilized at 300° C. which was held for 15 hours. Next the motor was heavily overloaded for a period of 45 minutes. The temperature of the windings reaching 506° C. After examination, the motor was retreated (2 more dips and bakes) and then given a long time thermal endurance test at a load producing 210° C. rise by resistance. Periodically, the motor was dismantled for examination and exposed to a high humidity and various insulation tests. This test continued for a total of 3376 hours at an estimated hot spot temperature of approximately 250° C. The test was ended by the rotor being stalled due to bearing failure. The rotor conductors melted and flowed over the windings as is shown in Figure 4. Detailed examination disclosed that the silicone varnish and insulation were still in operable condition and that the bearing was the cause of the trouble.

A very interesting series of accelerated thermal aging tests was made on a ship's service generator which was in mass production during the war. The stator winding of a 3 phase genera-

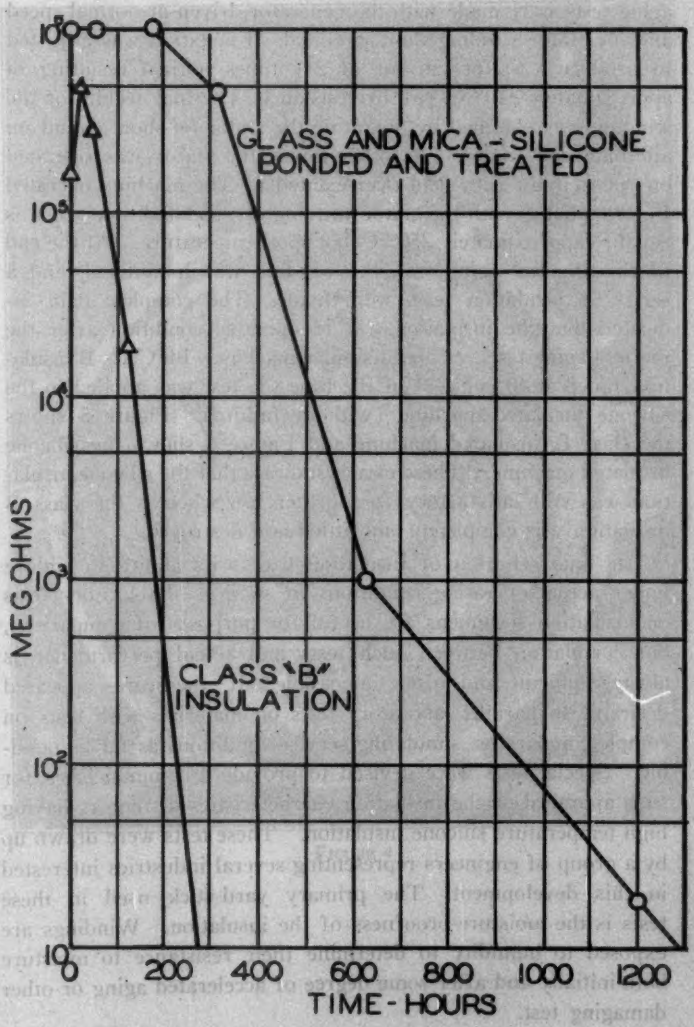

GLASS AND MICA - SILICONE BONDED AND TREATED
CLASS "B" INSULATION
MEGOHMS
TIME - HOURS
10^5
10^4
10^3
10^2
10
0
200
400
600
800
1000
1200

FIGURE 3

tor was completely insulated with silicone insulation. Thermal aging tests were made with the generator driven at normal speed and the stator winding short-circuited. Excitation was adjusted to produce a stator current of 2½ times normal resulting in approximately 210° C. rise by resistance. Thermal cycling of the winding was obtained by operating the stator on short circuit on alternate days only. (At other times, the stator was operated on open circuit with field over-excited.) The machine operated for 2966 hours with the stator winding at this condition which is equal to approximately 250° C. hot spot temperature. At the end of this thermal aging test, the winding was humidified, and a series of insulation tests were made. The complete data indicated that the insulation was in operable condition after the thermal aging tests. Later a similar machine with Class B insulation failed at 40 per cent of the time the test was applied to the silicone insulated machine (without failure). Figure 5 shows the class B, insulated machine and Figure 6 shows the silicone insulated machine. These clearly indicate that the silicone insulation was still satisfactory for further use whereas the class B insulation was completely embrittled and destroyed.

The final criterion of insulation life is its ability to endure under actual operating conditions in service. Laboratory tests on insulation specimens are useful for purposes of comparison, but correlation between such tests and actual performance is always difficult and often impossible. It, therefore, appeared desirable to parallel laboratory tests on materials with tests on complete apparatus, simulating service conditions as far as possible. Special tests were devised to provide a common basis for such appraisal of the insulation characteristics of motors having high temperature silicone insulation. These tests were drawn up by a group of engineers representing several industries interested in this development. The primary yard-stick used in these tests is the moisture-proofness of the insulation. Windings are exposed to humidity to determine their resistance to moisture both initially and after some degree of accelerated aging or other damaging test.

A large scale motor test program was undertaken jointly by Dow Corning and Westinghouse following this test procedure.

FIGURE 4

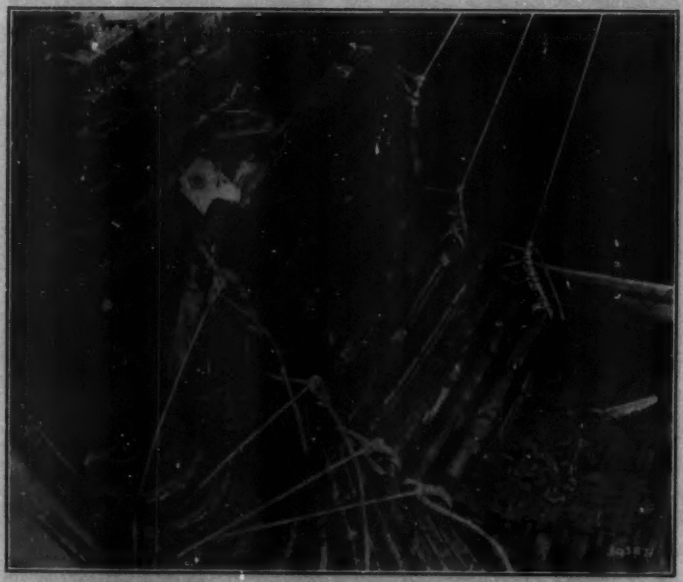


FIGURE 5

FIGURE 6

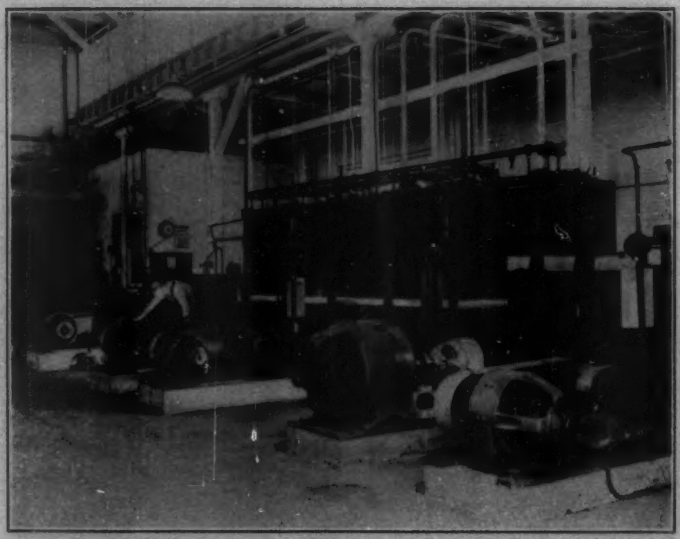


FIGURE 7

The principal objectives of this cooperative test program on actual motors were:

1. To determine the relation between operating temperature and life for silicone insulation between 200 and 300° C. (392 to 572° F). Given sufficient test points in this temperature range, reasonably accurate extrapolation both to lower and higher temperatures should be obtainable with assurance.

2. To obtain a comparison between the behavior of class A, class B, and silicone motors when subjected to the same type of test cycle.

3. To observe the cause of motor failure under accelerated test conditions, and to attempt to correlate the behavior of the insulation in motors with various types of laboratory tests on insulation components. If one or more laboratory tests could be found to correlate with the behavior of insulation in actual motors, then varnish and insulation development would be greatly simplified.

Figure 7 shows a number of motors undergoing this test.

The fundamental concept followed in these motor tests is that if a motor continues to operate while thoroughly wet with water, and if the moisture-proofness of the insulation (as measured by electrical properties of the wet insulation) does not change, the motor must be in good condition. It was thought that continued operation of the motors at high temperature would produce a sudden change in moisture-proofness. If so, this point could be considered the "minimum life" of the insulation. (In this connection, it should be pointed out that life of insulation is a variable thing and there is a range of time during which there is probability of failure rather than a sharp end point. This range is sometimes defined as a "90 per cent failure zone" with "minimum" and "maximum" life defining its limits.)

These tests have clearly demonstrated a tremendous advantage of silicone insulation over conventional forms when operated at elevated temperatures. The silicone insulated motors are exceeding the original life predictions by a considerable margin.

In evaluating the usefulness of silicone resins, it must be recognized that there is no point in increasing operating temperature unless some useful economic purpose is served. When reviewing the design of general purpose induction motors, it has been found that on open, splash-proof and semi-enclosed motors

where the performance of the motor rather than the temperature determines the amount of material used, the use of high temperature insulations will generally give no advantage. The size of these motors is determined by the pull-out torque, starting torque, starting current, efficiency and power factor. When these factors are maintained at currently acceptable values, the temperature rise is such that present class B insulation usually has sufficient thermal stability. There is more use for silicone materials on totally enclosed, and totally enclosed fan-cooled motors, as the present allowable class B temperature limits generally determine the amount of material. Frequently the design of these motors for maximum use of the electrical parts, results in temperatures in excess of the allowable class B temperature. In such instances, the use of silicone materials with the higher temperatures has been found advantageous. Redesign involving higher operating temperatures requires studying other problems. Air gaps may have to be larger to allow for more expansion of the rotor, bearings will have to allow for more shaft expansion. Furthermore, bearings and lubricants must operate at higher temperatures on many designs, especially on smaller motors.

A number of totally enclosed and fan-cooled motors have been made and tested experimentally. The performance of these motors is not the ultimate performance as the electrical parts used were those currently in use in class A and class B insulated machines. For a balanced high-temperature motor design with optimum use of the material, it is frequently necessary to change the relation of copper to iron, the quality of the iron, and length of air gap.

Two outstanding designers of large rotating electrical machinery have commented on this subject as follows:

1. There are many applications on large A.C. machines where the temperature margin of silicone insulation cannot be fully utilized, because efficiency and power factor decrease when the material is worked hard. However, there are cases where it can be used to advantage such as:

a) Enclosed fan-cooled motors where machines are now built much oversize, can be reduced to approximately normal size with good performance. This makes possible larger machines of this type than formerly.

b) Applications in high ambient temperatures such as occur in some boiler rooms and industrial applications—many of these can be taken care of with class B insulation at class A temperature rise limit, but silicone machines could be built, with class B temperature or higher, which would be smaller than the present machines.

c) There are other cases such as marine propulsion where weight and size are at such a premium that the loss in performance is offset by reduction in weight.

d) In certain limiting cases of high speed, machines could be built with silicones which are not possible with machines at class B temperatures.

2. There are a number of limitations in the design of D.C. machines, namely, temperature rise, commutation, overload capacity, and performance or efficiency. Silicone insulation eliminates one of these limitations, and in a general sense it can be said that there is a field for its use in any design in which temperature is the limitation.

a) Other examples of its field or application are some propulsion motors where the overload capacity and commutation characteristics are fixed by short-time ratings of power supply equipment. The same current ratings can be approached on a continuous basis by the use of silicone insulation.

b) In some applications, motors are required to operate over wide speed range at constant torque. The size of a motor is often determined by the ability of the machine to cool at low speed where the ventilation is very poor. If the temperature limit were removed, the machine could be designed on considerably smaller frame size.

c) Totally enclosed machine ratings are very definitely limited by temperature rise. Size of totally enclosed D.C. machines could be very materially reduced by the use of silicone insulation.

One of the major activities in the silicone insulation development program is of particular interest to Naval engineers. The complete redesign of a large ship propulsion motor (normally rated at about 3000 horsepower) was undertaken. The purpose

was to take full advantage of the temperature increase permitted with high temperature silicone insulation. Since it was desired to increase the shaft output using the same propeller, the motor speed was increased to enable the propeller to absorb the additional output. Therefore the total increase in horsepower was not attributable to the temperature increase permitted by silicone insulation. However, a fair evaluation of this appears to be more than 25 per cent increase in output attributable to the silicone insulation. This was accomplished without increase in weight.

Tests on silicone resins, silicone-treated materials and wound apparatus treated with silicone varnishes demonstrate that:

1) An unusually high order of thermal endurance is obtained.
2) The materials are usable with relatively minor variations in conventional processes, (mainly in baking temperatures).
3) That on some types of electrical apparatus, an appreciable advantage may be obtained in rating through operating at the higher temperatures when such are permitted by industry standards.
4) The moisture resistance of silicone varnish-treated coils is outstanding and there may be a field for its use where no advantage is taken of its high thermal stability.

It is important to recognize that the use of silicone resins in electrical insulation need not represent any radical departures from well established practices. Inorganic components of high temperature insulation have long been available and their characteristics proven. It was the organic bonds, impregnants and surface treatments which limited the thermal endurance of composite insulation containing mica, asbestos and fibrous glass. There is ample evidence that silicone resins used with these well known inorganic materials provide a new class of high temperature insulation.

It has been demonstrated by tests in the laboratory and many years of service experience that thermal aging is the most important single factor in insulation life. Only after such aging occurs does good insulation become vulnerable to other deteriorating influences. Differences in the thermal endurance of various types of insulation have been clearly demonstrated to be a func-

tion of the stability of their essential components. Therefore, the development of silicone resins promises great improvement in the weakest link in the insulation system. This property of improved thermal endurance may be utilized by designers of electrical apparatus in three important ways:

1) To reduce size and weight of some apparatus through increase in operating temperature.
2) To permit operation in a high ambient temperature.
3) To obtain increased insulation service life or reliability where it is desired to maintain conventional size, weight, and temperature.

COMPRESSED GASES IN THE U. S. NAVY.

LT. COMMANDER DAVIS R. DEWEY, II, U.S.N.R.*

The diversified applications of Navy compressed gases were of great value in World War II. With them the Navy has built, maintained and repaired ships, extinguished fires, refrigerated food, purified drinking water, combatted the malarial mosquito, and operated aircraft at extreme altitude. Gases have been used to kill, by propelling deadly fire from flame-throwers, and also to heal the sick and wounded, from front-line aid stations to established general hospitals. Gas requirements for these uses increased constantly throughout the war to take care of the increased size and operating range of the Fleet, and to serve the multitude of new needs which arose during this period. To illustrate the diversity of requirements, it was necessary to maintain in stock at Guam seventeen different kinds of gases, for local use and issue to other activities. Navy requirements for gases in the Pacific at the end of the war were 10 to 15 times as great as they were in the early part of 1943.

Until the 7th of December 1941, the U. S. Navy was accustomed to operating from bases with well established repair and supply facilities. The distribution of supplies from the continental U. S. was not a serious problem, and the relatively small Fleet requirements for gases were easily satisfied by routine shipments of cylinders filled by commercial concerns. As a result of the Japanese advances in the early part of 1942, it became apparent that we would have to wage an amphibious war on a larger scale than ever before attempted, in remote uncivilized areas many thousands of miles beyond the nearest base—Pearl Harbor —which was jammed by increased activity and still recovering from the Japanese attack. Two thousand miles from our operations were Australia and New Zealand, whose limited industrial capacity was already seriously overtaxed.

When the first South Pacific bases were established, the only supply of compressed gases was by cylinder shipments from the

* Heat Transfer Section, Bureau of Ships, Navy Department.

West Coast. Many of these cylinders were then sent to New Zealand for refilling. However, it soon became apparent that this method of supply would not be adequate. The requirements for oxygen and acetylene in ship repair and salvage, aviators breathing oxygen for combat operations, and carbon dioxide for fire-fighting grew rapidly, and showed every indication of still greater increases, as ships and aircraft extended their range and new bases were established farther forward. Losses of cylinders, under the primitive and difficult working conditions encountered, were tremendous. Enemy action accounted for a few shiploads. Cylinders returned to the States or sent to New Zealand for refilling were in transit for from 3 months to a year or more. Crude cargo handling facilities and lack of shipping space further aggravated the supply problems. In many cases cargo was unloaded across the beach and not alongside piers, requiring a transfer from the cargo ship to a landing craft alongside, which was then beached; and the cargo dragged ashore and loaded on trucks. Gas cylinders were a particularly slow and difficult cargo to move.

The situation just described resulted in serious shortages of gases, and their distribution was strictly rationed to only the most urgent uses such as battle-damage repair and combat air operations. Furthermore, there was a critical shortage of cylinders during the war, and it is estimated that 80 to 90 per cent of all Navy cylinders at any one time were in transit status, either full or empty.

Two approaches to the solution of the gas supply problem were undertaken early in 1943. The first approach was to provide immediate relief and avert disastrous shortages in the field. Four Army Air Force trailer mounted oxygen plants, one commercial type 20 meter oxygen plant, and two Army Engineer's trailer acetylene plants were sent to Espiritu Santo, New Hebrides, and to Guadalcanal, with detachments of personnel who had been trained in short intensive courses by the manufacturers of the equipment. At the same time, the first overseas shipment of liquid oxygen in bulk was sent from San Francisco to Espiritu Santo.

Simultaneously, as a longer-range approach to the problem, action was taken to develop and procure compact, portable oxygen,

acetylene and carbon dioxide plants which would be specially tailored to Navy requirements and advanced base operating conditions.

The emergency measures which were taken to supply oxygen and acetylene to the South Pacific proved successful and at the same time furnished valuable experience and brought to light many considerations of equipment design, spare parts allowances, plant organization and personnel training which contributed greatly to the efficiency of later operations. It was found essential that any plants shipped to a base should be complete and self-sustaining; for all base facilities were invariably overloaded.

In general, local knowledge of handling of gas cylinders was at a very low level, and base commanders promptly assigned to the crew of an oxygen plant, full responsibility for the maintenance and distribution of all gas cylinders at the base. This indicated the need for additional training of personnel before leaving the States.

In the operation of these early plants, improvisation, ingenuity and trading figured prominently. Tarpaulins on wooden frames were gradually replaced by Quonset huts; cylinder and valve repair shops were established; and occasionally a jeep or truck was acquired as part of the plant's working equipment. When a serious CO_2 shortage developed, an abandoned Marine Corps plant was located which had formerly produced hydrogen for a barrage balloon outfit long since inactivated. CO_2 was known to be a by-product of this plant. The plant was rebuilt using both American and Japanese parts from local junk piles, and was successfully operated for months before appropriate instruction manuals could be located.

The first overseas shipment of liquid oxygen in bulk was made in August of 1943. A 5500 gallon tank, weighing 50 tons when full, and containing the equivalent of 625,000 cubic feet of gaseous oxygen was shipped from San Francisco to Espiritu Santo. Personnel accompanied the shipment, with special converters for vaporizing the liquid oxygen and filling cylinders. When the tank arrived, only a few cylinders of oxygen were available at the base, and much of the steel cutting at the ship repair unit had to be done laboriously with power shears and hacksaws.

This tank filled 2000 cylinders and supplied the Island and Fleet until the first plants were erected and operating. Meanwhile, smaller tanks, 1350 gallon capacity, were designed and built for shipboard transportation; and a regular ferrying service was established from San Francisco to keep the larger tank filled. For many months liquid oxygen from this tank was used to fill all aviators' dry breathing oxygen cylinders in the South Pacific area. The ferry tanks were also used later to relieve temporary shortages in the Aleutians and at Guam.

At the time that the emergency measures discussed above were being taken, it was increasingly evident that future operations would cover a far greater expanse of territory, and that the advanced bases required would be much larger than anything yet established. Standardized plant designs were completed for self-sustaining units incorporating the features of reliability and portability, and procurement was expedited to obtain as quickly as possible sufficient plants to satisfy completely any remaining field shortages and have additional units in readiness for impending new operations. In stressing portability, mobility such as would characterize a trailer-mounted unit is not necessarily implied; but rather a plant whose individual shipment packages are of proper size and weight for handling by common cargo-handling equipment, and whose subdivided units are commonly mounted on skids, with as few interconnecting fittings as possible so that the plant may be unpacked, assembled and started up without undue delay. It was generally found that the majority of advanced base plants would operate in one place at full capacity for a year or more; and the increased accessibility of machinery, freedom from vibration, and more suitable working conditions of the stationary skid-mounted units showed pronounced gains in reliability and decreased maintenance. This has been especially so in the case of oxygen plants, where continual attention must be given to the operation and maintenance of heavy high pressure air compressors. Acetylene and carbon dioxide plants, having a minimum of heavy reciprocating equipment, have been found well adapted to trailer operation when electric drive is used with a separate skid-mounted diesel-electric power source. In special cases, trailer units were subsequently found to be advantageous in the early stages of an invasion operation.

Skid-mounted oxygen plants were in three major units; the air compressor and electric drive, the air cleanup, liquefaction and rectification system, and the liquid oxygen tanks with converters, and cylinder filling racks. Each separate unit could be packaged in a 7 feet cube, and the average unit weight was 5-6,000 pounds. The plant produced liquid oxygen, which was then taken from the storage tanks, vaporized in converters, and the resultant high-pressure gas charged into cylinders. Liquid oxygen was used for several reasons: it automatically guaranteed dryness for aviation breathing; it made available liquid oxygen and containers for emergency shipments by sea and by air; and the use of the converter simplified plant operation, decreased weight, and eliminated the extensive maintenance which is characteristic of oxygen compressors.

To permit the shipment of liquid oxygen by air, design requirements for the most common type of liquid oxygen tank specified that the size and weight should permit handling as air cargo in the Navy R4D, or Army C47 aircraft. This tank was about six feet long and 3½ feet in diameter, and carried the equivalent of about 80 standard 200 cubic foot cylinders of oxygen with a weight saving of 75 per cent. The tanks were produced after a successful experimental flight with an earlier model of smaller size, and the first one of the new tanks was shipped direct from the factory to the South Pacific for operational test. Fortunately, the test was eminently successful, for Marine fighter planes at Bougainville, 1000 miles north, had run out of oxygen and no immediate relief was in sight. The tank was filled, and after delays caused by Jap shelling of the Bougainville airstrip, was flown in and charged 75 cylinders on the spot. This method of supply was later established for routine operations in the China-Burma-India Theater.

It has been emphasized that field units should be self-sustaining. As advanced base conditions became generally more clearly understood, it was apparent that such plants could rely on established base facilities only for food, clothing, and personnel housing. This meant that each plant must be accompanied by its own housing, including cement, lumber, prefabricated Quonset huts, piping and wiring. It must include transportation such as jeeps and trucks. Complete diesel-electric power plants were necessary,

and equipment for setting up a water supply. A liberal allowance of tools and shop equipment was necessary. Each plant was accompanied by complete spare parts and routine operating supplies for the first six months of operation. All equipment and spare parts for a complete cylinder and valve maintenance shop were necessary to keep cylinders in service under rough handling conditions. Furthermore, each plant required a carefully selected and trained crew with capable officer supervision.

Each gas plant, as delivered, was the equivalent of a complete small factory, packaged for delivery to a base. This type of self-contained activity is known to the Navy as an "Advanced Base Functional Component". The catalog of functional components now includes every type of activity which may be required at a base, such as a 200 bed hospital, a 1000 man camp, a mine assembly unit, a supply depot, or a typewriter repair shop. Each component has all personnel, equipment and material required to establish itself and operate as part of the base. When a base was planned, its mission was outlined months in advance, and all necessary components were ordered to fulfill the work of this mission.

Oxygen plants were made up into components having a productive capacity of 2-3000 cylinders per month. Acetylene plant components could produce 2000 cylinders per month, and the carbon dioxide component 1200 cylinders per month.

The photographs accompanying this article show several of the compressed gas components.

In the first few months of 1944, enough components were assembled, shipped and put into operation to take care of the majority of existing gas shortages in the Pacific. However, new operations, such as those in the Marianas and Philippines, were in the making and advanced bases planned for these areas were to be even larger than those already established. For each operation all components had to be carefully scheduled according to landing date, weight of shipment, shipping space or cubage required, and number of personnel. When the planning was completed, each contributing Bureau was told when and where to assemble its share of the component equipment for shipment overseas. To insure readiness for these assembly dates, it was necessary to estimate requirements far in advance, and to stock

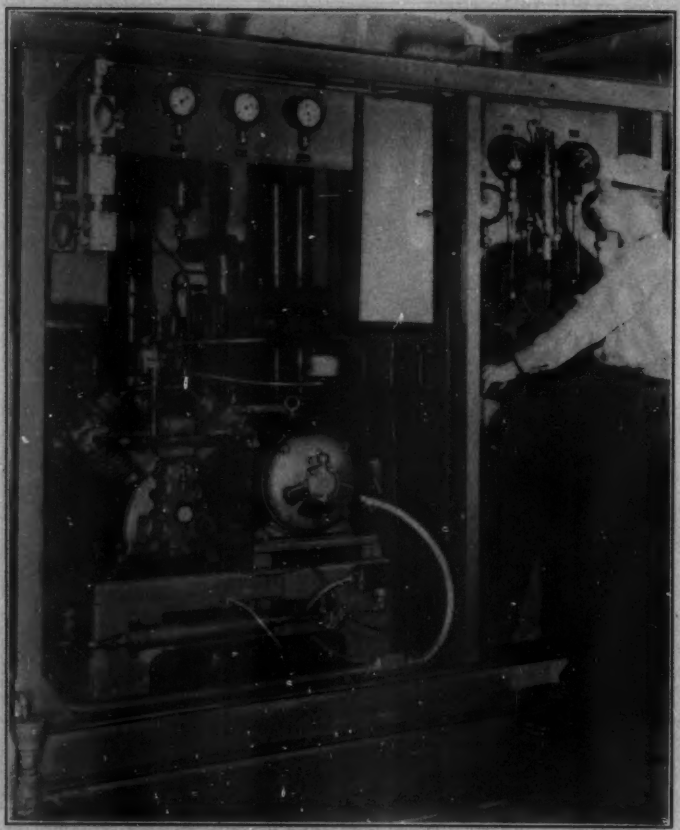
adequate quantities of all equipment in inland depots. The scheduling of specialist personnel was in many ways a more serious problem, as these men had to be intensively trained, and much of this training could be forgotten if they were kept waiting in personnel pools.

The importance of careful selection, training and assignment of compressed gas personnel cannot be overemphasized. A well-trained, enthusiastic and intelligent crew will build and improvise in the field to keep plants running where others have to shut down and send frantic dispatches to the States for special parts. Conversely, the finest plant cannot keep up production at the hands of a carelessly picked or poorly trained group, and frequently becomes a serious hazard. Through the helpful cooperation of the compressed gas companies, it was possible to locate many of their plant personnel who had joined the Navy. In this way an experienced nucleus of officers and men was found. However, as requirements grew, only about 3 per cent of personnel needed had civilian experience. The other 97 per cent had to be picked from other chemical and mechanical trade groups and given special training in all aspects of Navy compressed gas plants.

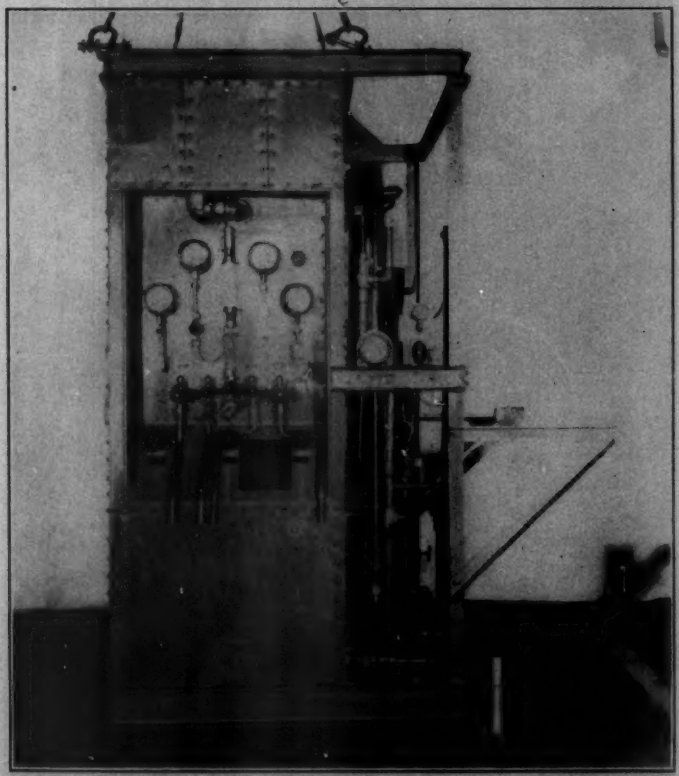
While shortages were still critical, these men were trained by the concerns producing the equipment, on the factory grounds. In many cases the urgency was such that test runs on new plants were made by trainees, and the plants and crews "graduated" almost simultaneously.

In the summer of 1944 a centralized Naval Training School for Compressed Gases was established at Camp Peary, Williamsburg, Virginia. Representative operating units were set up, comprising every type of gas producing and handling equipment which would be encountered in the field. Wherever possible, the school simulated advanced base conditions. The plants were housed in Quonset huts and the men lived in smaller adjoining huts. The power supply was the standard 75 Kw. diesel-electric sets. The students were thoroughly trained in the theory of manufacture of gases, the operation and maintenance of oxygen, acetylene and carbon dioxide plants, the diesel-generator power equipment, and the inspection and maintenance of cylinders and valves. The total curriculum for all courses covered almost 6 months, and was

TWO 150-GALLON LIQUID OXYGEN TANKS LOADED INSIDE A C-47 AIRCRAFT, READY FOR FLIGHT FROM JORHAT, ASSAM, INDIA TO MYITKYINA, BURMA.

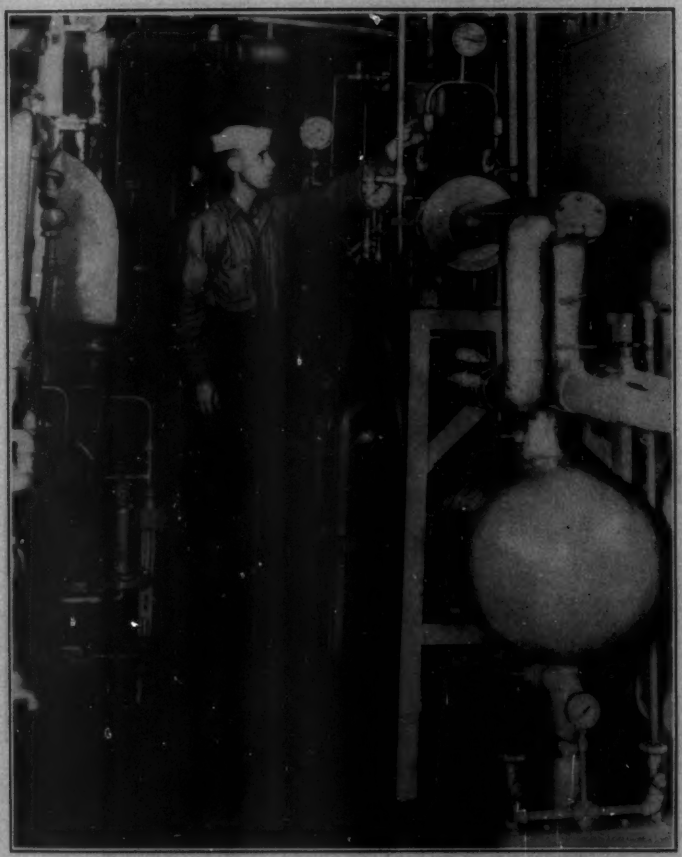


BADGER OXYGEN PLANT—FRONT VIEW OF RECTIFYING COLUMNS. NOTE FREON COMPRESSOR AT LEFT. WEIGHT OF UNIT IS THREE TONS.



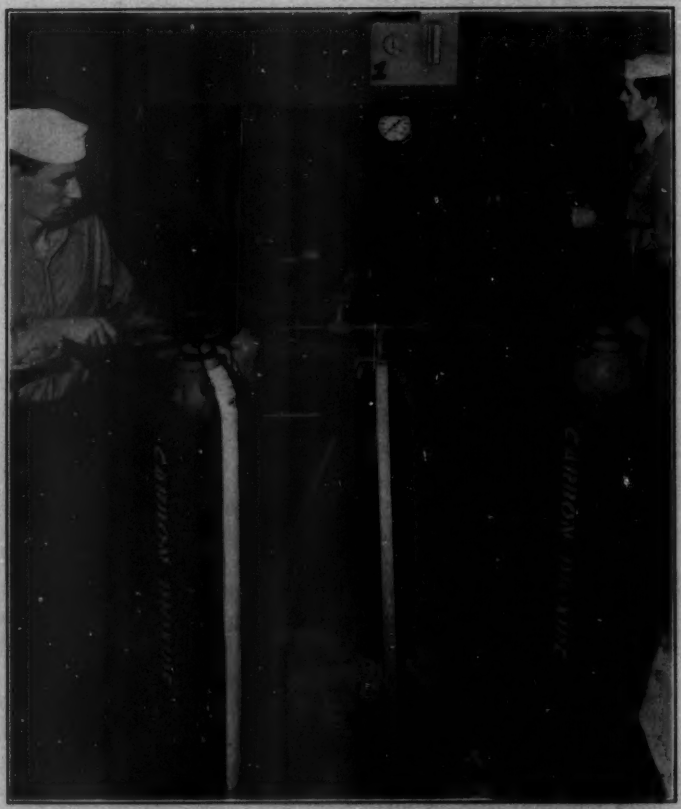
BADGER OXYGEN PLANT—DEVELOPED FROM DESIGNS PREPARED BY THE AIR REDUCTION COMPANY FOR THE NATIONAL DEFENSE RESEARCH COMMITTEE.

LINDE OXYGEN STORAGE AND FILLING EQUIPMENT. AIR TRANSPORT STORAGE TANKS, CAPACITY 150 GALLONS, ARE AT THE LEFT. THE CONVERTERS ARE IN THE CENTER WITH FILLING MANIFOLD AT THE RIGHT. A HOT WATER HEATER FOR CONVERTER OPERATION IS IN THE BACKGROUND.

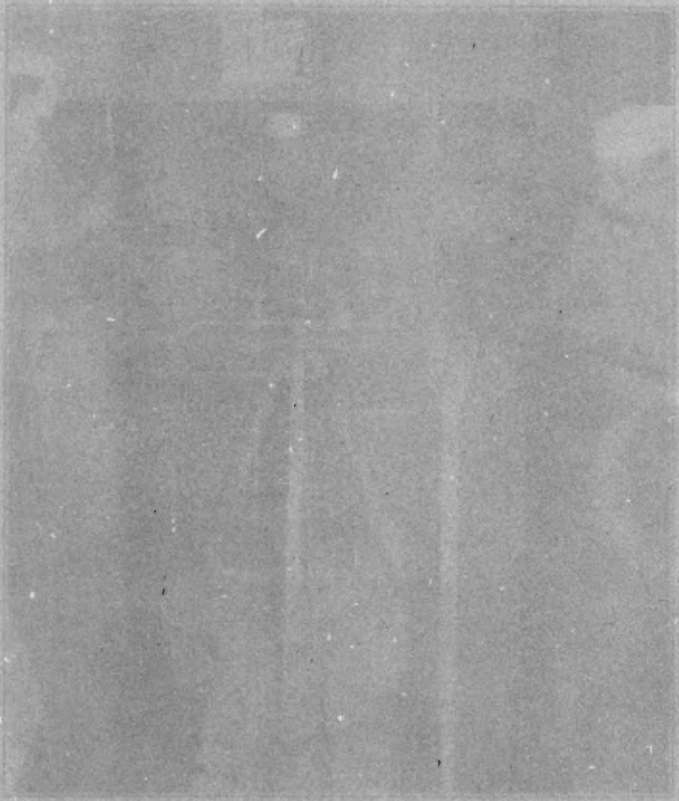


INTERIOR VIEW OF GIRDLER TRAILER MOUNTED CO_2 GENERATING PLANT. PLANT PRODUCES 150 LBS. OF CO_2 PER HOUR FROM FLUE GAS FROM OIL BURNERS INTEGRATED WITH PLANT.

CO_2 Plant, Guadalcanal—Side View of the Dupont Methanol Plant Which Produces CO_2 and Hydrogen.



CARBOX LIQUID CO_2 STORAGE TANK AND TRANSFER PUMP—THIS EQUIPMENT IS USED TO STORE CO_2 AND SERVICE THREE TON AIRCRAFT CRASH TRUCKS AND FILL CYLINDERS AND FIRE EXTINGUISHERS.



so subdivided that an individual could qualify for general cylinder and valve maintenance and for the operation of one type of plant after the first 9 weeks of training. In this way emergency requirements for operators could be satisfied without maintaining a large pool of unassigned gas specialists who were qualified in all types of plants.

The selection and classification of prospective trainees was particularly important. Men sent to the school were picked on the basis of civilian experience and skill, general and mechanical aptitude. In this way, the already extensive training program was not seriously hampered by having to teach simple mechanical fundamentals to men who had just left high school or had been employed entirely in non-mechanical trades. Any man considered not qualified after the first 2 or 3 weeks of training was returned to general duties. Those who successfully graduated from the school were given a specialist rating of "MMG", or "Machinists Mate, Gas", and thus were earmarked for compressed gas duties at the base to which they were assigned. The results from this selection and training program were outstanding in every way. Field units set up by these crews exceeded the rated productive capacity of their equipment. In spite of the inherently dangerous nature of much of the work there were no fatalities in any Navy gas plant. These men established an enviable record of production, safety, and service throughout the Pacific advanced bases.

Several new and interesting features in plant design, component organization, personnel training and methods of gas distribution were brought about by special conditions encountered in the field. After the first successful operational flight of liquid oxygen, it was obvious that this new method could be most profitably used in the supply of oxygen to the Army Air Forces and Engineers in China and Burma where ground travel was generally impossible and weight savings on air cargo were of paramount importance. Two complete Navy oxygen plant components, together with one acetylene plant, were set up, at an Army air base several hundred miles northeast of Calcutta, and operated by a picked group of Naval officers and men. In addition to supplying local needs, these plants delivered air shipments of liquid oxygen over the "hump" to China, and eastward to Burma. Small converters at

the receiving points were used for cylinder filling. Deliveries were equivalent to 1000 standard two hundred cubic foot cylinders of oxygen per month for nine months, and a total round trip weight saving of 2,000,000 pounds of air cargo was achieved in this time.

Although the main emphasis in the Pacific was on the establishment of reliable stationary plants, trailer-mounted equipment proved to be of great value in the early stages of an invasion. The Okinawa campaign gives an interesting case history of such an application. In preparing for this operation, a trailer-mounted oxygen plant was packed with necessary spares and tools, thirty days supply of chemicals, food rations, tentage, and household gear for the crew. This plant was landed and towed across the beach to its operating site on D plus 31, and six hours after arrival there it had filled its first cylinder of oxygen. The unit and men were totally self-sufficient, and operated without shutdown to supply critically needed oxygen for repair work, construction, and high-altitude flying until shore and unloading facilities were well enough established to permit a more permanent installation.

In the manufacture of CO_2, the Navy was requested to supply low pressure, low temperature liquid CO_2 for Army fire trucks assigned to B-29 strips in the Marianas. These trucks would dump several tons of CO_2 at once to extinguish an airplane crash fire. Starting at first with improvised field equipment, plants were modified and standardized to provide for production and storage of low pressure liquid CO_2. As a result of this work, the lives of many B-29 crews were saved on Guam, Saipan and Tinian.

Improper handling and identification of gas cylinders by the users has been the cause of many tragic and destructive accidents. The crude nature of advanced base cargo facilities, the urgency of unloading operations, and lack of appreciation of potential dangers gave rise to many unsafe practices, such as hoisting piles of full cylinders in cargo nets, and stowing oxygen, acetylene and other gases together at crowded supply points. Such examples of mishandling were spotted and corrected quickly by trained personnel. Incorrect identification of gases was a far more serious problem.

The average commercial user of compressed gases seldom requires more than two or three different gases in his plant. These gases are generally supplied separately and little difficulty is experienced by the customer in putting each to its proper use. Naval supply and repair activities, however, must service all types of ships, aircraft, and other equipment, and must, therefore, receive and distribute all gases required for a wide range of uses. To the majority of personnel, one cylinder looked very much like another, especially if the climate and handling conditions had obliterated all conspicuous markings. A mistake made at any point in the long supply line, or by the final user, would produce disastrous results—such as charging an airplane's oxygen breathing system with CO_2, or charging, up to a point, a ship's refrigeration plant with oxygen.

To prevent such accidents, the Navy undertook a widespread program of education and standardization. Compressed gas personnel at bases and on Service Force Staffs issued technical instructions to all activities. The Navy's color code for painting cylinders was adopted by all services operating in the Central and South Pacific areas, for gas cylinders were filled and distributed to users on a joint basis, regardless of cylinder ownership. This color code has now been developed in detail and adopted by the Army Air and Service Forces for all Army cylinders. The Navy has now specified additional markings. The name of the gas is indented in the valve body, stencilled in two inch letters on opposite sides of the cylinder, and shown by decalcomanias on the cylinder shoulder.

The Navy has adopted new designs of non-interchangeable valve outlets and connections for different gases, as developed by the Compressed Gas Manufacturers' Association, so that future users can get into trouble only through a rare combination of ingenuity and stupidity.

At the end of the War, Navy gas plants in the Pacific had a monthly production of 65,000 cylinders or 13,000,000 cubic feet of oxygen, 14,000 cylinders or 3,150,000 cubic feet of acetylene, and 5500 cylinders or 275,000 pounds of CO_2. These installations covered the Pacific from the Aleutian Islands to the New Hebrides, New Guinea, the Solomons, the Philippines, the Marshalls, the Marianas, and Okinawa. The plant in India was

a major supply source in that area. In all, 40 officers and 850 men had been trained, and plants had been set up and operated at nineteen advanced bases. Some of these installations, notably those at Guam and Okinawa, included several components, and required close to a hundred men each for full-time operation. In July 1945, over 80 per cent of the gas used in the Pacific areas was produced in the field. Gases had been made available for all needs, and thousands of tons of shipping space had been released to other uses.

Since the defeat of Japan many advanced bases have been reduced or inactivated. On bases retained for postwar, the Navy will continue to operate and maintain compressed gas plants. For the most part, portable plants have proven sufficiently reliable and efficient for future use as permanent operating units, although a few installations of commercial type stationary oxygen plants will be operated where local demands are high.

A small oxygen plant has been installed on a repair ship. This plant was designed to operate at sea under conditions of rolling and pitching. The success of this design was dramatically proven when the plant operated continuously at full production during a three-day typhoon. A plant to recover, purify, and bottle CO_2 from ship's stack gases has recently been installed and operated on another repair ship, showing that plants of this type are not necessarily limited to shore installations.

Work on compressed gases is by no means finished. Overall supply methods, local distribution systems, and new uses for gases are under constant review. Plant designs must be developed or modified for increased efficiency and special operating conditions. Pipe lines are replacing cylinder handling in Naval Shipyards and drydocks. Educational programs, on paper and film, are teaching men in all Naval activities to appreciate the value of compressed gases, and to exercise judgment in handling them. Through this effort, and with the generous cooperation of industry, improvements in detailed design and standardization of all aspects of gas handling equipment are increasing the safety and usefulness of all Navy compressed gas applications.

DISCUSSION OF THE PAPER:* "FORMATION AND REMOVAL OF SLAG FROM SUPERHEATER TUBES OF MARINE BOILERS," BY FREDERICK R. HOCK.

By Frank E. Clarke.

The author's paper attempts to apply the conclusions of Harlow (1) and of Corey, Cross and Reid (2) to explanation of slagging of the exterior of Naval superheater tubes. Neither reference is applicable to the Naval problem since both are concerned with external corrosion of tubes, not evident in Naval superheaters, in coal fired boilers, while the Navy burns oil. Harlow mentions external deposits in economizers and air heaters but not on superheater tubes. Upon this insecure foundation the author has erected an hypothesis of chemical reactions, interreactions, catalysis and decomposition which does not appear too closely related to the observed conditions and the reported data. A simple physical explanation appears to coincide with the data available to the writer.

The icing effect of cold rain suggested the writer's explanation. When wires or similar metal surfaces are at or very close to the freezing point (melting point) of water, droplets of rain congeal on the metal surface, coating it with ice. At higher metal temperatures there is no tendency for the water to freeze and at lower temperatures the frozen particles rebound instead of adhering. The behavior of molten ash particles entrained in the furnace gases and threading their way through boiler tube-nests may be very similar. All but the most refractory ash constituents exist as liquid droplets in the furnace, where the ambient temperature is 2500 degrees to 3000 degrees F., and will remain liquid until the entraining furnace gases have been cooled below the melting point of the entrained particles. A molten droplet will congeal and rebound from a metal surface at temperatures several hundred degrees cooler than its melting point but on

* The opinions expressed in this discussion are those of the writer and do not necessarily reflect the views of the Navy Department or of the Naval service at large.

(1) Engineering, Vol. 156, pp. 497-500 (1943) 17 December.

(2) Trans. A. S. M. E., Vol. 67, No. 4, pp. 279-302 (1945) May.

striking a surface whose temperature is in the vicinity of its melting point, the droplet will wet the surface and congeal in situ.

The writer's examination of superheater slags has shown obvious stratification of the deposits, as shown in Figure 1. Separate analyses of the tube-side and fire-side layers discloses differences in composition illustrated in the following table.

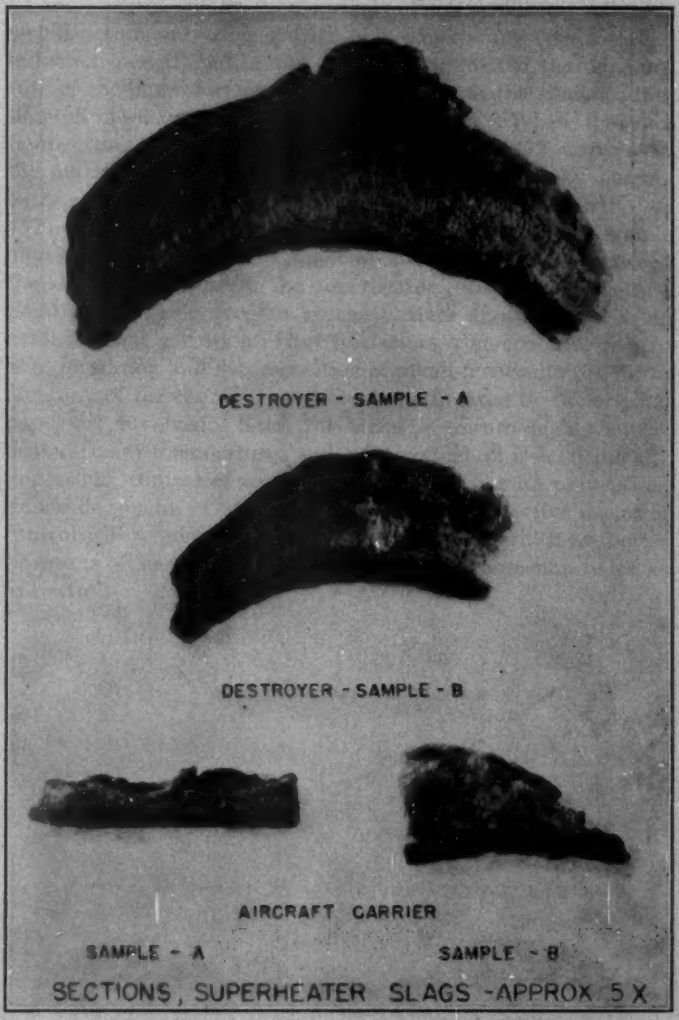
	Superheater Slags			
	Destroyer Composite—A and B		*Aircraft Carrier Composite—A and B*	
Probable Constituent	*Furnace-Side Layer*	*Tube-Side Layer*	*Furnace-Side Layer*	*Tube-Side Layer*
Silica, SiO_2	0.74	0.67	1.06	0.73
Vanadium Oxide, V_2O_5	20.60	54.10	15.30	45.03
Iron Oxide, Fe_2O_3	3.20	2.26	6.20	3.38
Nickel Oxide, Ni_2O_3	5.75	Trace	5.28	.....
Chromic Oxide, Cr_2O_3	.....	.....	4.75	.....
Sodium Sulfate, Na_2SO_4	42.29	35.95	47.64	44.75
Magnesium Sulfate, $MgSO_4$	10.72	1.87	10.28	.....
Calcium Sulfate, $CaSO_4$	6.56	0.71	8.02	1.53
*Water	8.55	3.44	1.62	2.62
Carbon	0.62	0.36	0.56	1.50

* Probably water of crystallization.

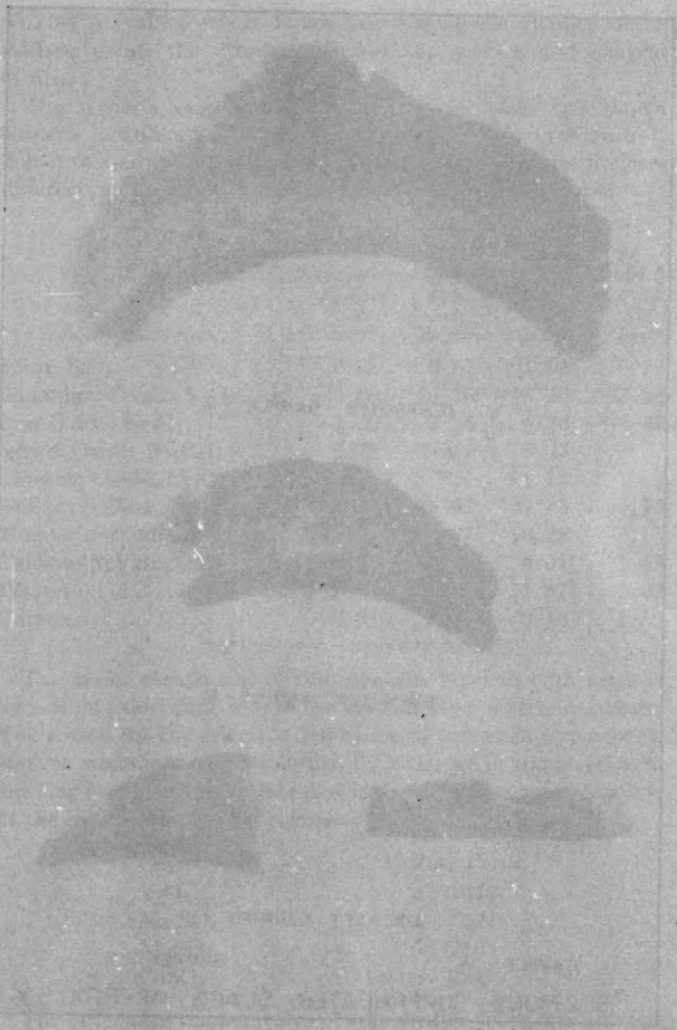
The major constituent of the tube-side layer in both cases is vanadium oxide while that of the fire-side layer is sodium sulfate. The reason for the selective deposition of some ash constituent, such as vanadium oxide, followed by a change in composition of the slag is evident from the following table of the melting points of the principal ash constituents.

Compound	*Melting Point, °F.*
V_2O_5	1472
Na_2SO_4	1624
$MgSO_4$	2165
$CaSO_4$	2642

The outer-skin temperatures of superheater tubes operating at steam temperatures of 900 degrees to 1000 degrees F. approach the melting point of vanadium oxide. With boilers continuously steamed at high rates, slight fluctuation in steam flow will permit an occasional molten particle of vanadium oxide to wet, adhere



SECTIONS, SUPERHEATER SLAGS -APPROX 5 X



to and congeal on the tube surface. Such accidental adhesion would permit only slow growth of a slag coating (the so-called induction period) but as the coating accumulated the temperature of the outer surface would rise to permit the similar adhesion of more and higher melting materials. When the skin temperature of the accumulation approaches 1472 degrees F. the outer surface would become a semi-molten, sticky magma entrapping solid particles to accelerate the rate of growth.

The writer believes that superheater slagging is a simple physical phenomenon dependent upon the relationship between the skin temperature of the superheater tube and the melting point of inorganic droplets in the furnace gases. There is no evidence that corrosion of tube exteriors, conversion of SO_2 to SO_3, formation and decomposition of alkali-ferric sulfates, or, in fact, any of the chemical reactions hypothecated by the original paper are involved. Since the trend is toward higher superheated-steam temperatures and ash-free fuel-oil is economically impossible, control of superheater slagging, not its prevention, should be sought. Determination of the most effective means of control will require study but the investigator will have better prospects of success if he understands the phenomenon he seeks to control.

DISCUSSION OF ARTICLE BY ALAN OSBOURNE AND ROBERT M. MEYER ON "APPLICATION OF A RELAXATION METHOD TO THE SOLUTION OF SIMULTANEOUS EQUATIONS OF THE TYPE THAT OCCUR IN MULTI-ANCHORED PIPE THERMAL STRESS COMPUTATIONS,"

PUBLISHED IN THE MAY, 1945, JOURNAL OF NAVAL ENGINEERS.

BY WILLIAM H. WATKINS (CIVIL MEMBER).*

The method of relaxations for solution of structural problems has been used in this office[1] for a period of years, but has gradually given way to other methods. The method works well in many structural problems, and the fundamental equations are particularly useful in solving rigging problems, or others where there are an unusual number of members attached to one or more joints. A great advantage of this method for this type of problem lies in the fact that, in setting up the essential equations, the number of unknowns in the system of equations is independent of the number of members.

As a method of solving a set of simultaneous linear equations, it is generally successful, or can always be made successful by suitable combinations of relaxations, but sometimes involves considerably more work than other methods, since it does not always converge quickly. The amount of work required for obtaining an acceptable answer can roughly be judged by an examination of the coefficients of the unknowns. In general, a speedy and simple solution by the relaxation process will be obtained if each coefficient in the main diagonal of the matrix representing the equations is much larger than the other coefficients in the same row or column. If two or more coefficients in the same row or column are of the same order of magnitude, group relaxations involving the unknowns to which these coefficients apply are probably necessary, if an early convergence is to be obtained. The difficulty of securing convergence in exceptional

* Scientific & Test Group, Code 254, Puget Sound Naval Shipyard.
[1] Puget Sound Naval Shipyard, Design Branch, Scientific & Test Group.

cases may be easily demonstrated by the following set of equations with equal coefficients:

$$x + y + z = 6$$

$$x - y - z = 0$$

$$x - y + z = 2$$

If these equations are set up and solved by the method of relaxations, applying the general rule only (namely, reducing the largest coefficient each time), it will be impossible to obtain convergence. This condition is independent of the size of the unknowns. For example, if we substitute for constants or right hand values, the values 16, 4, and 6, respectively, we still fail to obtain convergence without resorting to a group relaxation. If in the first case we apply the group relaxation $x = 3$, $y = 2$, $z = 1$, we immediately converge to the solution; similarly in the second case, group relaxations of $x = 10$, $y = 5$, $z = 1$ converge immediately to 0. Another group relaxation applying to any set of constants consistent with real values of the unknown is (a) $x = y = \frac{1}{2}$, (b) $x = -z = \frac{1}{2}$, (c) $z = -y = \frac{1}{2}$.

An interesting application of the relaxation or iteration process is a recently developed electrical computer[2] for solving linear simultaneous equations using electrical circuits for setting up the values of the coefficients and constants on resistances or potentiometers. The voltages or currents indicated on the instrument are then balanced out by adjusting potentiometers representing the unknowns. The values of the unknowns when all circuits are finally balanced are read from the potentiometer settings.

In considering whether relaxation is a satisfactory method for solution of simultaneous equations, the outline presented by Leland[3] of the requirements of a good method of solution might well be referred to. These are:

1. Universally applicable to short and long problems.

2. Various steps should be identical so that they may be performed mechanically.

3. Should be short as practicable to avoid unnecessary work.

[2] "A Computer for Solving Linear Simultaneous Equations," by Berry, Wilcox, Rock, & Washburn, Journal of Applied Physics, Vol. 17, April 1946, pages 262-272.

[3] "Practical Least Squares", by Ora M. Leland, page 40.

4. Should provide checks at frequent intervals throughout the computations in order that errors may be disclosed and corrected without a great deal of re-computation.

Following the outline of steps as presented by the authors, the experience here with the relaxation method has been:

(a) Preparation of table operations: Uncertainties exist in that it is not easy to anticipate the combinations of operations desirable. While this does not interfere with the process, as the table can easily be prepared to permit additional combinations of operations being entered as their need becomes evident, it does delay the solution, since several relaxations generally have to be made before suitable group relaxations are evident.

(b) Preparation of the relaxation table: By including all components at all joints and keeping track of the changes in reaction of each, a check can be maintained on the arithmetical work. This is not of much value in the simple system of Figure 1, but is of value in some of the more complex problems. It may involve an appreciable amount of additional calculations and entries.

(c) Adding the relaxations from the relaxation table to obtain total movements in each direction at each joint. Forces are generally computed and applied to the original equation to check the agreement.

The principal disadvantages found in the relaxation processes are as follows:

1. There is a considerable amount of preliminary computation and tabulation required prior to undertaking the process after the fundamental equations are obtained. Copying figures into tables is frequently the slowest part of any straight-forward computing process and should be reduced to a minimum.

2. The processes of working out relaxation operations are frequently long, if the remainders are to be reduced to a few per cent of their original values. Also, preparation of relaxation table involves considerable copying coupled with mental adding and subtracting. The process, however, is well suited to slide rule work.

3. The process, to be most successful, requires experience and judgment in that suitably chosen group relaxations are necessary to speed a solution which otherwise would be very slow in converging to acceptable answers. It requires close supervision, if turned over to computer to carry out.

A method which has been found to be generally superior, provided a fully automatic computing machine is available, is that of Prescott D. Crout.[4] This process takes full advantage of the ability of a calculating machine to accumulate the algebraic sum of products of two numbers, such as (a.b + c.d − e.h—etc.). This sum, which is accumulated in the middle dial of the machine, can be immediately divided by another number. With a symmetrical system of equations, with real coefficients as is the case in most structural problems, the work is considerably reduced over the general case. A check column can be carried along and the work checked as it progresses. It has the advantage that the process is mechanical and can be turned over to a computer for solution, and there is a relatively small amount of copying to be done. In some instances, a useful advantage is that additional load conditions can be easily solved with very little additional work. A disadvantage is that it sometimes requires carrying computations to extra significant figures to get satisfactory answers, which cannot be fully anticipated in advance.

The method involves writing the set of equations to be solved as a matrix, called the "given matrix." From this is computed the "auxiliary matrix." Each element in the auxiliary matrix requires the accumulation in the computing machine of the sums of products of the elements in the same column above the desired element by those in the same row, to its left. If the element is a diagonal element or is below the main diagonal, this sum subtracted from the element in the "given matrix" in the same position as desired element determines the desired element in the auxiliary matrix. If to the right and above the main diagonal, the process is exactly similar, except that the accumulated sum of products is divided by the value of the diagonal element. There are the same number of elements in the auxiliary matrix as in the given matrix. The "final matrix" is computed in a somewhat similar manner. Denoting the elements of a given matrix by G_{ij}, those of the auxiliary matrix by A_{ij}, and those of the final matrix by F_{ij}, the method is contained in the following equations:

$$A_{ij} = G_{ij} - \sum_{k=1}^{i-1} A_{ik} A_{kj}$$

[4] "A Short Method for Evaluating Determinants and Solving Systems of Linear Equations with Real or Complex Coefficients," by Prescott D. Crout. Transactions of A. I. E. E., 1941.

$$A_{ij} = G_{ij} - \sum_{k=1}^{j-1} A_{ik} A_{kj}, \text{ if } i > j$$

$$A_{ij} = \left[G_{ij} - \sum_{k=1}^{i-1} A_{ik} A_{kj} \right] \frac{1}{A_{ii}}, \text{ if } i < j$$

and

$$F_{i1} = A_{i,n+1} - \sum_{k=i+1}^{n} A_{ik} A_{ki}$$

Where any Σ whose lower limit exceeds its upper limit vanishes. For a complete description of this method references should be made to the original paper or available abstracts.[5] This method, applied to the second example given in the paper, is shown in Table I, where the computation is carried out to a somewhat greater number of significant figures than necessary; and Table II where its computations are carried out to 4 significant figures all the way through. The final matrix is written as a one row matrix instead of a one column matrix.

A casual comparison of the amount of work involved in solving this particular problem is indicated by the following tabulation of the number of the various operations of multiplication, division, addition, and copying figures shown for each method. Under the matrix method, the number of operations required both with and without a check column is drawn. Using a check column, the final check by substitution is omitted, although it is recommended that a final check by substitution always be made, regardless of the method of solution. This is quite easy to do where an automatic calculating machine is available.

Comparison of the total amount of work involved in obtaining solutions by the relaxation method and matrix method outlined above has generally shown an appreciable saving of time for the matrix method. It is believed that it is well worth while that engineers become acquainted with this rapid and relatively simple process wherever access to a modern fully-automatic 8 to 10 bank computing machine is available.

[5] Methods No. MM-182 and MM-183, Marchant Cal. Mach. Co., Oakland, California.

COMPARISON OF OPERATIONS REQUIRED IN SOLUTION OF GIVEN EXAMPLE BY RELAXATION AND MATRIX METHODS.

Item	*No. of Multiplications to Be Made*	*No. of Divisions to Be Made*	*No. of* Items to Be Added*	*No. of† Items to Be Entered*
Relaxation Method:				
Original Equations	..	..	...	42
Operations Table	66	6	72	114
Relaxation Table	144	..	144	318
Relaxation Summary	6	..	24	18
Computation of Unknowns	6	..	12	24
Check by Substitution	36	..	6	6
Total	258	6	258	522
Matrix Method—without Check Column:				
Original Matrix	..	..	...	42
Auxiliary Matrix	50	21	20	42
Final Matrix	15	..	5	6
Check by Substitution	36	..	6	6
Total	101	21	31	96
Matrix Method—Check Column:				
Original Matrix	..	..	42	49
Auxiliary Matrix	65	27	46	49
Final Matrix	30	..	10	12
Total	95	27	98	110

* Not including summation of products which is assumed to be taken care of in automatic calculating machine.

† Not including descriptions or keys to operations.

TABLE I

GIVEN MATRIX

δx	δy	δz	ϕx	ϕy	ϕz	Constants ($x10^{+8}$)	Check
−25.330 29	− 1.387 83	+13.681 20	− 0.011 81	− 0.381 81	− 0.013 20	+16.687 356	+ 3.243 816
− 1.387 83	−24.639 14	+18.002 07	+ 0.684 17	− 1.085 62	+ 0.070 98	−21.039 912	−29.395 282
+13.681 20	+18.002 07	−71.484 01	− 0.697 42	+ 1.937 87	+ 0.137 93	− 1.706 189	−40.128 549
− 0.011 81	+ 0.684 17	− 0.697 42	− 0.051 41	+ 0.031 27	+ 0.000 19	+ 0.622 222	+ .577 212
− 0.381 61	− 1.085 62	+ 1.937 87	+ 0.031 27	− 0.129 03	+ 0.006 08	− 1.083 196	− .704 236
− 0.013 20	+ 0.070 98	+ 0.137 93	+ 0.000 19	+ 0.006 08	− 0.026 09	+ 0.122 942	+ .298 832

AUXILIARY MATRIX

δx	δy	δz	$4x$	$4y$	$4z$	$= (x10^{+8})$	Check
−25.330 29	+ 0.054 789 35	− 0.540 112 25	+ 0.000 466 24	+ 0.015 065 36	+ 0.000 521 12	− 0.658 790 56	− 0.128 060 75
− 1.387 83	−24.563 102	− 0.702 374 07	− 0.027 879 91	+ 0.043 345 99	− 0.002 919 13	+ 0.893 787 82	+ 1.203 960 66
+13.681 20	+17.252 486	−51.976 924	+ 0.004 286 54	− 0.018 930 16	− 0.008 485 45	+ 0.156 092 45	+ 1.137 963 43
− 0.011 81	+ 0.684 817	− 0.222 801	− 0.031 356 81	+ 0.078 254 68	− 0.045 242 65	− 1.184 372 51	− 0.151 363 15
− 0.381 61	− 1.064 712	+ 0.983 932	− 0.002 453 82	− 0.058 311 90	− 0.111 285 35	+ 9.251 302 76	+10.140 022 06
− 0.013 20	+ 0.071 703	+ 0.181 163	+ 0.001 418 67	+ 0.006 489 26	− 0.024 456 03	+ 1.491 384 95	+ 2.491 384 21

FINAL MATRIX

− 0.650 269	+ 0.682 336	+ 0.347 508	− 1.853 844	+ 9.417 272	+ 1.491 385

CORRESPONDING FORCES

− 650.3	+ 682.3	+ 347.5	− 1853.8	+ 9417.3	+ 1483.4

NOTE: Maximum difference on substitution values of unknowns in original set of equations is for 3rd equation where substitution results in a value of 1.706 202 instead 1.706 189.

TABLE II

δx	δy	δz	ϕx	ϕy	ϕz	k
			ORGINAL MATRIX			
-2.533^{+1}	-1.388^{0}	$+1.368^{+1}$	-1.181^{-2}	-3.816^{-1}	-1.320^{-2}	$+1.669^{+4}$
-1.388^{0}	-2.464^{+1}	$+1.800^{+1}$	$+6.842^{-1}$	-1.086^{0}	$+7.098^{-2}$	-2.104^{+4}
$+1.368^{+1}$	$+1.800^{+1}$	-7.148^{+1}	-6.974^{-1}	$+1.938^{0}$	$+1.379^{-1}$	-1.706^{+3}
-1.181^{-2}	$+6.842^{-1}$	-6.974^{-1}	-5.141^{-2}	$+3.127^{-2}$	$+1.900^{-4}$	$+6.222^{+2}$
-3.816^{-1}	-1.086^{0}	$+1.938^{0}$	$+3.127^{-2}$	-1.290^{-1}	$+6.080^{-3}$	-1.083^{+3}
-1.320^{-2}	$+7.098^{-2}$	$+1.379^{-1}$	$+1.900^{-4}$	$+6.080^{-3}$	-2.609^{-2}	$+1.229^{+2}$
			AUXILIARY MATRIX			
-2.533^{+1}	$+5.480^{-2}$	-5.400^{-1}	$+4.662^{-4}$	$+1.507^{-2}$	$+5.211^{-4}$	-6.589^{+2}
-1.388^{0}	-2.456^{+1}	-7.024^{-1}	-2.788^{-2}	$+4.337^{-2}$	-2.920^{-3}	$+8.939^{+2}$
$+1.368^{+1}$	$+1.725^{+1}$	-5.198^{+1}	$+4.286^{-3}$	-1.893^{-2}	-3.485^{-3}	$+1.561^{+2}$
-1.181^{-2}	$+6.848^{-1}$	-2.228^{-1}	-3.136^{-2}	$+7.849^{-2}$	-4.525^{-2}	-1.182^{+3}
-3.816^{-1}	-1.065^{0}	$+9.839^{-1}$	-2.461^{-3}	-5.824^{-2}	-1.114^{-1}	$+9.254^{+3}$
-1.320^{-2}	$+7.170^{-2}$	$+1.811^{-1}$	$+1.419^{-3}$	$+6.486^{-3}$	-2.446^{-2}	$+1.492^{+3}$
			FINAL MATRIX			
-6.505^{+2}	$+6.822^{+2}$	$+3.476^{+2}$	-1.854^{+3}	$+9.420^{+3}$	$+1.492^{+3}$	

NOTE: Superscript refers to number of places decimal point is displaced to right or left.

NOTES.

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—British Motorship, May, 1946.

SOME RESEARCHES IN INTERNAL COMBUSTION PRIME MOVERS.
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THE ESCHER WYSS-A.K. CLOSED CYCLE TURBINE.
Its Present Development and Future Prospects.
—British Motorship, April, 1946.

THE FUTURE OF NUCLEAR POWER.

This article by John Archibald Wheeler, Associate Professor of Physics at Princeton University, appeared in the May 1946 issue of Mechanical Engineering. It outlines briefly the process which will be used for an atomic power plant, and discusses some of the limitations.

The atomic-energy plants of the Hanford Engineer Works are located near what was once the little agricultural town of Hanford, Washington (Figure 1). The plants lie in a country of sagebrush and sand on the bank of the beautiful blue Columbia River, about halfway between the Grand Coulee Dam and the Bonneville Dam. The author can testify that one could not ask for a quieter, smoother-running, or more reliable plant, having followed its operation from its start-up on September 26, 1944, over the period of the past 16 months. It can now be stated that the possibility of the controlled release of atomic energy does not have to be proved—it is an accomplished fact.

Hanford Built as Plutonium Plant.

The Hanford plant was not built to generate nuclear energy, however. Its purpose was to synthesize a new chemical substance, plutonium, element 94, to make atomic bombs. The production of heat in this reaction was not merely incidental; it was a positive drawback in the program to make as much plutonium as possible. For example, the production of as much as 1 Kg. of plutonium per day requires the release of an amount of heat between 500,000 Kw. and 1,500,000 Kw. From these figures it will be understood that problems of heat transfer and heat dissipation controlled the capacity of the Hanford plants to synthesize plutonium. These problems are engineering problems.

In the nuclear-energy plant of the future the liberation of energy in the form of heat or otherwise will be the primary objective and the production of plutonium or other substances subject to nuclear fission will be secondary. But the most difficult problems will still be engineering problems: (1) To transfer heat from the chain-reacting structure, the so-called pile, to a cooling fluid and (2) to convert this heat into usable energy. The problems of nuclear physics which enter into the design of the power-producing pile of the future have in principle been solved. The concensus of opinion of the industrial men and the scientists who have been connected with the uranium project is that, assuming freedom to develop, it is only a question of time before we shall have an industrial technology of nuclear energy which can pay its own way. The time interval will depend most of all upon the engineering talent which is applied to the solution of the engineering problems of the pile.

Chain-Reacting Structure or Pile of the Future.

Nuclear physics indicates that the power plant of the future will be in six important ways quite similar to the present Hanford piles of which Figure 2 is typical.

Nuclear Fission. The heat-releasing reaction will be fission, the division of a heavy atomic nucleus into two parts of approximately equal mass. We can exclude from consideration other transformations such as the reactions of lighter atomic nuclei which provide the heat of stars. These reactions occur at a significant rate only at temperatures between 1,000,000 and 50,000,000 degree. That it will not be feasible to make industrial plants operating at such enormous temperatures is clear enough when one observes the destructive power of a body as hot as an atomic bomb. Nuclear fission, on the other hand, requires for its production, not high temperatures but only bombardment of the nucleus in question by the elementary particle or "neutron" Figure 3.

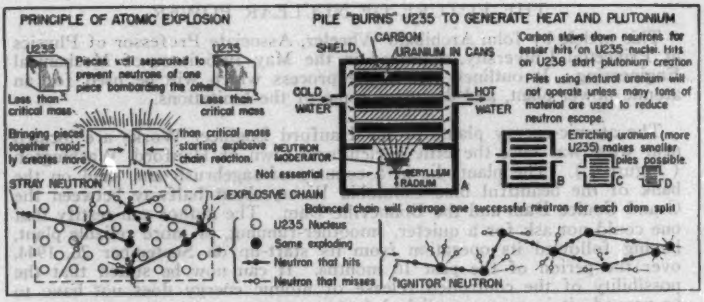

PRINCIPLE OF ATOMIC EXPLOSION
U235
U235
Pieces well separated to prevent neutrons of one piece bombarding the other
Less than critical mass
Less than critical mass
Bringing pieces together rapidly creates more than critical mass starting explosive chain reaction.
STRAY NEUTRON
EXPLOSIVE CHAIN
PILE "BURNS" U235 TO GENERATE HEAT AND PLUTONIUM
SHIELD
CARBON
URANIUM IN CANS
COLD WATER
HOT WATER
NEUTRON MODERATOR
Not essential
BERYLLIUM
RADIUM
A
Carbon slows down neutrons for easier hits on U235 nuclei. Hits on U238 start plutonium creation
Piles using natural uranium will not operate unless many tons of material are used to reduce neutron escape.
Enriching uranium (more U235) makes smaller piles possible.
B
C
D
Balanced chain will average one successful neutron for each atom split
U235 Nucleus
Some exploding
Neutron that hits
Neutron that misses
"IGNITOR" NEUTRON

FIGURE 3.—SCHEMATIC DIAGRAM OF OPERATION OF A PILE WITH URANIUM SLUGS, SHIELDING, AND PROCESSING OF SLUGS.

(Neutrons issue from slugs of uranium as a consequence of fission and pass out into surrounding graphite matrix. There they are slowed to energies at which, on re-entry into the uranium, they have a good opportunity to be captured into the fissionable isotope U-235 and induce further fission. By this arrangement the chain reaction is kept going. Most of the neutrons which are not utilized in this process are captured by the inactive uranium isotope, U-238, and cause it to transform into the fissionable material, Pu-239, plutonium, which is the goal of the Hanford process. From supplement to *American Scientist*, October, 1945, courtesy McGraw-Hill Publishing Company, Inc., New York, N. Y.)

Without inquiring more about the nature of this particle just now, we can note that not only is one neutron sufficient to produce fission, but also that the act of fission produces in turn several new neutrons. The release of these particles at the time of splitting will not come as a surprise to anyone who has observed carefully the mouth of a slowly dripping water faucet. As each big drop breaks away, several tiny droplets are formed and thrown out from the point of division. This rather minor side reaction in the process of breaking off a water droplet is all-important in the act of fission for it provides several neutrons, each of which can produce a further fission process, provided that more nuclei are available which are susceptible to nuclear fission.

Basic Material. The foregoing requirement brings us to the second feature of the present chain-reacting units which will be preserved in the piles of the future; we require as source of energy a substance which undergoes fission with high probability when struck by a neutron. There are only a few nuclear species which satisfy this condition. They are all comparable in atomic weight to uranium, or heavier than it. The two most prominent examples of such fissionable materials are plutonium-239, the most important variety of the new and 94th chemical element; and uranium-235, the variety of nucleus which is present to 1 part in 140 in ordinary uranium. Both nuclear species play an important part in the Hanford piles. The U-235 undergoes fission and thus maintains the nuclear chain reaction. Most of the extra neutrons not needed for continuance of the chain reaction are used in synthesizing the new fissionable element, plutonium. The pile of the future must operate by fission of one or the other of these two substances or of some nuclear species very near to these two in the periodic system of the elements.

Fissionable Material Must Be Replaced. Unfortunately, none of the desired fissionable species of nuclei exists in nature in anything but in-

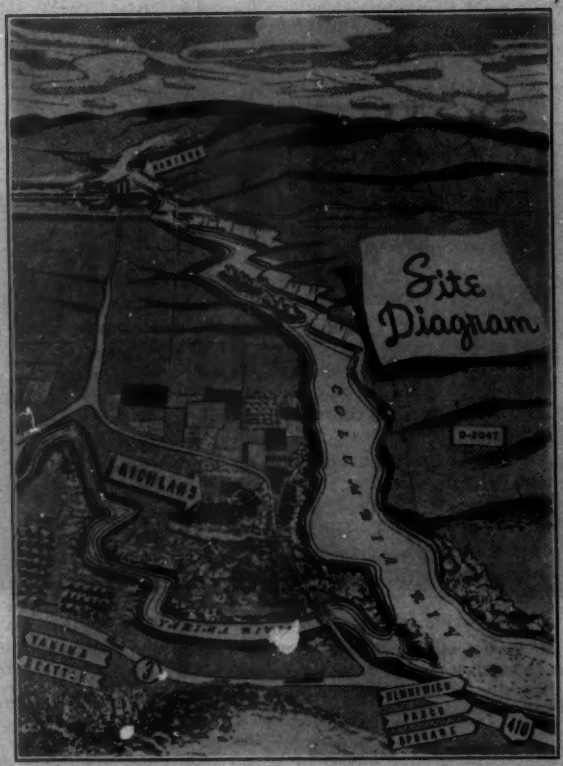


FIGURE 1.—VIEW OF PLUTONIUM PLANT AREA IN STATE OF WASHINGTON, SHOWING 30-MILE SEPARATION BETWEEN PILE AND SEPARATION AREA AT HANFORD AND RESIDENTIAL VILLAGE AT RICHLAND.

(From Smyth report, "Atomic Energy for Military Purposes.")

FIGURE 2.—ONE OF PILE AREAS AT HANFORD SITE.

(The obvious powerhouse and pumping station illustrate the similarity between a nuclear and a standard power plant. The actual building in which the pile is located cannot be pointed out for security reasons. From Smyth report, "Atomic Energy for Military Purposes.")

significant traces, except U-235. Furthermore, the task of separating U-235 from ordinary uranium is difficult and expensive. Consequently, it is reasonable to ask of the pile of the future a third feature, that it should synthesize by a suitable side reaction as much as possible of the fissionable material which is burned up during operation. Here again the Hanford piles point the way. At the same time that their operation burns up the one fissionable material, U-235, it creates the new and equally desirable fissionable species, Pu-239.

In partial explanation it may be said that the process of synthesis starts with the very abundant but otherwise useless nuclear species, U-238. This species, by capture of a neutron and a resultant sequence of changes, is transformed into the wanted Pu-239. One may ask, if the heat given off in this reaction was such a source of engineering difficulty in the war program, why bother to go to all the trobule to destroy one perfectly good bomb-making material in the course of making another one? The answer is simple. It was much easier to separate out from the original element, uranium, the new and chemically distinct element, plutonium, than it was to separate two forms of uranium from each other. The objective of the Hanford program was to avoid the problem of separation of two different species of the same chemical element and to replace it by the problem of chemical separation of two distinct elements.

It paid to do this in spite of the heat-transfer difficulties which were encountered and in spite of the fact that all the heat was thrown away. However, in the pile of the future, where the heat energy will be the primary point of interest, considerations of economy will give us the same incentive we had to produce fissionable material from an otherwise relatively useless raw material such as the abundant U-238.

In future attempts to accomplish this regeneration process there will be one or other of two possible outcomes. It may be that each day of operation of the pile of the future will burn up, let us say, 1 Kg. of the original fissionable material and regenerate out of U-238 or similar inert material possibly only 0.9 Kg. of new fissionable material such as plutonium. In this case the plant can continue operation only if we supply from outside each day 0.1 Kg. of new fissionable material. This requirement will prevent atomic energy from becoming quite as cheap as we should like to have it.

The other possible outcome is more favorable to economy of raw materials. In every day of operation in which we destroy 1 Kg. of fissionable material we synthesize from an inert substance more than 1 Kg. of new fissionable material, say, for example, 1.1 Kg. In this case we leave 1 Kg. of the new product in the plant to make up for the losses of the day and remove the other 0.1 Kg. to help start up a new pile; or if necessary, to help make atomic bombs. In case we can achieve this outcome, there is no need for us to supply new fissionable material to our plant from the outside, except to get it started. After it is in operation we could even feed it as raw material uranium from which all of the active constituent, U-235, has been extracted, although it would be cheaper to use natural uranium. The plant itself will convert the inactive uranium to fissionable material for use in the chain reaction. Evidently we have only to design a plant with sufficiently good regeneration characteristics in order to use for power purposes all of the uranium, not merely the rare constituent U-235.

Continuous Supply of Raw Material. However good the regeneration characteristics of our future power plant, or in other words, however efficiently we use the raw material, we must obviously still have a continuous supply of raw material. This requirement brings us to the fourth point of similarity with the Hanford chain-reacting units. It will be necessary in the future as in the past to use for raw material

either uranium itself or possibly, we may hope, some other element of comparable abundance in the earth, but with a neighboring or higher position in the periodic table of the elements. The only such substance which exists in nature is thorium, an element apparently somewhat more abundant than uranium. Consequently, the pile of the future will be expected to use as source of energy either uranium or possibly thorium.

Chemical-Separation Plant. There is a fifth requirement on the nuclear power plant of the future which is not so obvious as those which have gone before. Associated with the power unit there should be a chemical plant for the treatment both of the raw material and of the fissionable material after they have been exposed in the pile. We will expect different locations to be chosen for these two materials to get the best results. But as time goes on, fissionable material will be synthesized within the relatively inert raw material. If this fissionable substance is allowed to stay where it is, it will eventually be struck by a neutron and be caused to split, but to split at a point in the pile where the neutrons which it gives off will not be used with full effectiveness. To avoid this loss of efficiency, which might be serious, we must expect to have to withdraw the raw material periodically from the unit and extract from it the newly synthesized element. The two components that result from this chemical separation process will then be sent back to their proper places in the pile, the raw material to one location, the fissionable material to another.

This is not the only task which the chemical plant will have to perform. The fissionable material will also experience changes which will call for its reprocessing. The products of nuclear fission, elements of medium atomic weight like barium, lanthanum, xenon, rubidium, selenium, tellurium, silver, ruthenium, will accumulate and poison the chain reaction by absorbing the neutrons which we want for more productive purposes. Consequently, we will expect to have to remove these by-products of the reaction from time to time from the fissionable material, whether this material is U-235, Pu-239, or something else.

Of course the separation plant of the Hanford pile does only a part of what we demand of the separation plant of the future. It withdraws from the working material only the plutonium which was required for atomic bombs. It is designed to produce plutonium by the most straightforward possible means, with no attempt to serve as a power plant. Consequently, it does not need to prepare the working material, uranium, for reintroduction into the unit.

Protection Against Radioactive Radiations. The final major point of resemblance between the future plant and the Hanford pile is the requirement of protection of human beings against radioactive radiations. Not only does the act of fission liberate fast and penerating neutrons, but it also releases electromagnetic radiations which have the same character as x rays and even greater piercing power. These so-called gamma rays, together with the neutrons coming from a pile in full production, have near such a reactor an intensity more than a million times as great as can be tolerated biologically by the human organism. It is necessary to surround the pile with a shield which will cut down the intensity of these radiations to a negligible level. One can imagine the difficulties which arise in obtaining complete protection when it is considered that there must be openings in the shield for the entrance and discharge of the cooling fluid and for the insertion and the removal of uranium or other working material before and after irradiation. It is gratifying to be able to say that these structural problems not only can be solved, but that they have been solved at the Columbia River plants, and solved in a very satisfactory way.

Shielding a Limiting Factor in Future Applications.

However, it is necessary to report that the required shielding weighs a great deal. Even for a unit generating as little as a 100 Kw. the shielding has a thickness of a number of feet and weighs in the order of magnitude of 50 tons. Unfortunately, there is no device at our disposal to overcome this difficulty. The principles of shielding are very simple and straightforward. What counts is essentially the product of the thickness and the density of the protective material. This circumstance means that even with the densest practical materials there is a minimum required thickness for the shield.

It might just be possible to carry such a shield through existing railway tunnels on a locomotive driven by nuclear power, but the prospects for train propulsion are not bright. Atomic power appears to be quite out of the picture for automobiles. The same conclusion applies also to airplanes, at least until the weight carrying capacity reaches ten to a hundred times the present figure. On the other hand, it is quite in order to count on nuclear energy for driving ships or for running a stationary electric power plant. In neither application does a heavy shield cause too much difficulty.

Fortunately, the required weight of the protective material does not increase greatly with power level. Consider a shield thick enough to reduce to a biologically acceptable intensity radiations from a pile which in the absence of shielding would be a million (10^6) times too intense. Increase the power output of this pile tenfold, so that the radiation is ten million (10^7) times the acceptable level. Then it is only necessary to increase the thickness of the shield in the ratio of 7 to 6 or 17 per cent to shield the 10 times more active pile.

Some emission of radiations continues even after the chain reaction is brought to a halt. Some of the products of nuclear fission, elements of medium atomic weight, are radioactive when formed. These active materials are present in the irradiated uranium which is discharged from the Columbia River piles, and therefore in the uranium which is received by the chemical separation plant at Hanford. What is true of this separation plant will be true of the chemical plant associated with all future piles; shielding is indispensable. To give an impression of the magnitude of the shielding problem, it may be mentioned that there was poured at Hanford 780,000 cu. yd. of concrete. Of course this amount of material was distributed over several plants, and only a part of it went for shielding purposes. The magnitude of even a single plant is necessarily so great that it may possibly not be economically feasible unless it is designed to produce at least as much as perhaps 100,000 Kw. of power.

Cooling Fluid for Atomic Power Plant.

In the Hanford piles the cooling fluid is water; in the future power plant this fluid will be some substance capable of going to much higher temperatures than water without requiring very high pressures, Table I. High pressures would require heavy piping; but every foreign material introduced into the pile absorbs neutrons and makes it that much more difficult to run the unit efficiently. In contrast to the pressure, the temperature of the pile is a matter of relative indifference from the point of view of the nuclear-chain reaction. It matters little to the fission fragments whether the temperature of the uranium is a few hundred degrees or more than a thousand degrees, for their own instantaneous energy at the moment of production is equivalent to more than a billion degrees. It will therefore be reasonable to operate at as high a temperature as our materials of construction will stand and gain all the thermodynamic

TABLE 1 NEUTRON ABSORPTION IN CONSTRUCTION MATERIALS[a]

Substance	Cross section per nucleus of most absorbent element	Adopted density	Neutron path for 10 per cent absorption
Water..... (H)	0.25×10^{-24} cm²	1.00	6.3 cm
Heavy water.....	.....	1.11	....
Lithium..... (Li)	58×10^{-24} cm²	0.53	0.039 cm
Beryllium..... (Be)	$<0.03 \times 10^{-24}$ cm²	1.8	>19 cm
Beryllium oxide....	.....	...	....
Boron..... (B)	500×10^{-24} cm²	2.5	0.0015 cm
Graphite..... (C)	$<0.06 \times 10^{-24}$ cm²	1.6	>22 cm
Fluorocarbons..... (F)	0.05×10^{-24} cm²	1.8	>30 cm
Sodium.....	0.38×10^{-24} cm²	0.95	11.2 cm
Magnesium.....	0.31	1.74	7.9 cm
Aluminum.....	0.42×10^{-24} cm²	2.7	4.2 cm
Iron.....	1.6	7.8	0.78
Nickel.....	3.6	8.7	0.33
Copper.....	2.6	8.9	0.48
Silver.....	58	10.5	0.03
Cadmium.....	2950	8.6	0.0008
Mercury.....	325	13.6	0.0079
Lead.....	0.32	11.0	10
Bismuth.....	0.33	9.8	11
Uranium.....	(~6)	18.7	~0.37

[a] Based on data of H. Volz, *Zeitschrift für Physik*, vol. 121, 1943, p. 201. These data are taken from this German source because more recent American data are not available.

NOTE: The figures in the right-hand column give the average path length which a completely slowed, or "thermal," neutron can travel in typical materials before experiencing a 10 per cent chance of absorption. From this table it is evident that such a material as mercury is not suitable for transferring heat from hot uranium in a pile of Hanford design to a turbine or other power-generating device. The same table shows that sodium, lead, or bismuth are cooling materials which might be acceptable from a nuclear viewpoint. Boron and cadmium are seen to be materials effective in controlling the rate of a nuclear-chain reaction.

efficiency that we can in our power plant. The cooling fluid, whatever it is, will then be led out to a heat exchanger. There its energy will be turned over to water or mercury or some other substance capable of driving a turbine or other prime mover. That is the power plant of the future.

Use of Radioactive Materials.

A great deal has been said about the use of radioactive substances without adequate realization of the hazards involved. It is feared that the country as a whole is not going to realize how great are the dangers of the uncontrolled use of such materials until a number of people shall have lost their lives, either through their own carelessness or through the negligence of others. The extraordinary health and safety record of the plutonium project has drawn attention away from the difficulties which were encountered, and which were solved to guarantee the safety of all the workers on that project. We cannot be sure in the future that the organizations which will deal with these materials will have the same appreciation of the importance of safety as the du Pont Company and the Monsanto Company, nor that they will have the same sound medical advice which was provided by the so-called Metallurgical Laboratory of the University of Chicago.

The problems of adequate control of the use of radioactive substances in the future appear too great to be handled on a merely voluntary basis. It may very well be necessary to have all chemists who deal with radioactive materials specially trained in regard to safety precautions, and licensed and bonded to the state or national government. Let us hope that some such system is set up while we still have the sound practice of the plutonium project as a working model, and before anyone has lost his life through lack of proper legislation.

The radiochemists of the future will have many radioactive materials at their disposal. Most of the chemical elements of medium atomic weight created by the act of fission are formed in a radioactive condition. Other elements can be made radioactive by exposure in a chain-reacting pile. For the active substances which will be obtained by these means there will be a number of specialized uses, such as the painting of watch dials, the examination of heavy castings by means of penetrating radiations, the treatment of the blood disease known as leukemia. But it is probable that our greatest benefits from these materials will be indirect, and will come from our having a powerful tool for the study of chemical and physiological changes. Tagged atoms will give us information which we can get by other means only with the greatest difficulty, or not at all. Among such tools one of the most important will be the tagged atom or radioactive nuclear species known as carbon-14.

The uses of radioactive substances, in spite of their importance, require relatively small amounts of material. We cannot expect that the radioactive business will be one with a large income. This business will be subordinated to power-plant activity, not the other way around. We have to count on the power plant to pay its own way as a power plant, except as it serves as the source of bomb-making materials.

Military Aspect of Atom is Paramount.

Just as the production of radioactive materials is a small matter compared to the release of nuclear power, so in turn this power must today and forever in the future be considered as a matter secondary to the military applications of the atom. It is certainly desirable for us to have in the future nuclear power plants as a source of electrical energy which is suitable for general use in special sections of this country and for special uses in the whole of the country. But it is essential to the future of the United States and the United Nations that it have this law-enforc-

ing power ready at hand. It is for this reason most of all that we must see that this country develops a strong technology of nuclear energy.

A good deal has been said, and very rightly so, about the destructive power of the atomic bomb. The discussions, however, tend to give the false impression that it is only necessary to have a certain stock of these bombs on hand to stop future transgressors. This conclusion may be correct in some cases, but if there is anything which has been shown by the history of the last two wars, it is that one cannot count on a stockpile of anything to stop the aggressors who are really important. What is required is productive capacity and know how; and productive capacity means big atomic power plants.

Let us analyze what is meant by productive capacity and know how. What advantages did this country have in the atomic-bomb project during the war? (1) The scientists; but other countries had them also. (2) Imaginative and courageous support, to the everlasting credit of President Roosevelt and to our own good fortune. But imagination is no longer required in the future to see that this field requires support. (3) We had the industrial know how and productive capacity to do the job. We could have furnished Japan not only with all our so-called purely scientific information, most of which they had anyway, but even with the blueprints of the final installations, and still the Japanese would not have been able to make atomic bombs.

Where could they have made the special aluminum parts that were required, parts that required for their manufacture the most advanced facilities possessed by the aluminum industry in any nation in the world? How would they have got the facilities to convert uranium compounds into uranium metal, a problem that was solved only through the experienced advice and help of industrial concerns working closely with our best metallurgical laboratories? Where would they have got the enormous quantity of graphite, let alone the purity of graphite required to construct the chain-reacting piles of the Columbia River project?

The facilities to make these things cannot be built up over night. They are the creation of thousands of intelligent and skillful men working over a period of years. It would have done us no good if we had had locked up in the safes in Washington the blueprints for graphite ovens, the drawings for aluminum-fabricating machinery, the procedures for smelting uranium. What counted was our industrial know how and our manufacturing facilities. With them the blueprints could, if necessary, be dispensed with. Without them the blueprints would do us no good.

Security Lies in Industrial Development of Nuclear Energy.

Our true security lies not in secrecy, but in a strong industrial development of nuclear energy.

This point is emphasized because some of the legislation now under consideration in Washington would make it practically impossible for any industrial concern to enter the field of nuclear power generation. The author is quite in sympathy with the conclusion that the Government must have control over all fissionable materials. That is an obvious condition for all security. But there is danger that many are now overlooking an equally obvious condition for our security, i.e., the development of the nuclear industry. The Government cannot do this at all satisfactorily. It is not an engineering concern. Every dollar spent by the Government in encouraging industry to enter this new field will be worth ten dollars spent by the Government's trying to do it itself. We cannot expect it to have all the know how of drawing aluminum tubing, smelting uranium metal, manufacturing graphite. We must open the new field to all qualified industries and promote a healthy competitive development. That is the way our security lies, and the engineers are the ones who will bring about this development.

LIGHT ALLOYS FOR SHIPS' SUPERSTRUCTURES.

This article is an extract from a paper presented by W. Muckle before the North East Coast Institution of Engineers and Shipbuilders as it appeared in the British Motor Ship for May 1946. It presents the advantages to be gained in reduced power by saving weight through the use of light alloy superstructures on merchant vessels.

While in many cases it may be desirable to increase the cargo-carrying capacity of a vessel by the saving in weight occasioned by the use of light alloys, it does not always follow that this is the best way of using the weight saved. The introduction of light alloys into the superstructures of a vessel can result in a modification of the design for a given displacement with a consequent reduction in power. The influence on the design may be considered in the following steps:—

(a) The reduction of top weights results in the centre of gravity of the loaded ship being lowered.

(b) In consequence of (a) the breadth of the ship may be reduced so as to maintain the same initial stability.

(c) If the reduction in the height of the centre of gravity does not permit of the beam being reduced sufficiently to reduce the displacement by the amount of weight saved, then a reduction in block coefficient is possible.

(d) These alterations in breadth and block coefficient result in a reduction in structural weight which allows further reduction of displacement.

(e) The reduced displacement, with its influence on length displacement ratio, block coefficient and breadth/draught ratio, means that the power can be reduced for a given speed.

(f) Reduced power means smaller machinery and fuel weights for the same speed.

In this method of using the weight saved, the vessel must earn sufficient additional money by its reduced fuel bill to pay for the cost of the light-alloy arrangement. Letting

F = total fuel used per annum,
C_f = cost of fuel per ton,
S = percentage saving of fuel,

then a balance is reached when the increased cost per annum due to using light alloys is equal to the cost of the fuel saved per annum, i.e., when

$$n\,(w_a\,p_a - w_s\,p_s) = C_f \times F \times s.$$

From this expression a "permissible price of light alloy per ton" may be obtained which is

$$p_a = \frac{\dfrac{C_f \times F \times s}{n} + w_s\,p_s}{w_a}$$

In this no allowance is made for the first cost of the machinery being less, as it probably would be due to the reduced power. Nor is any allowance made for, say, the reduced tonnage due to the smaller dimensions and finer block coefficient. This would have some small effect on the running costs. Again, no account has been taken of the possible reduced upkeep cost when light alloys are employed. It is not possible to arrive at any simple formula for p_a since the saving in power and fuel must be bound up in a very complex way with the original saving in weight, the speed, type and service of the vessel. It is possible, however, to give some broad, general conclusions.

The arguments given above can be applied to any type of merchant vessel where the weight saved is being used to alter the dimensions and so reduce the power required for a given speed. A little consideration will show that they do not apply with equal force to all types of ship. The power for a given speed is some function of the displacement and the reduction in power will be greater, the greater the percentage reduction of displacement. It is evident then, that the benefit will be the greatest in those vessels where the original saving in weight represents an appreciable percentage of the displacement.

The percentage of displacement saved will be greatest in those vessels where the weight of structure represents a large portion of the displacement. In the purely cargo vessel the cargo deadweight is the largest portion of the displacement, and the structural weight may represent only about 20 per cent of the displacement. To reduce the displacement by 3 per cent in this type of vessel would necessitate a reduction of 15 per cent of the structural weight. In a vessel, however, where the structural weight represents, say, 40 per cent of the displacement, the displacement could be reduced by 3 per cent by a reduction of the structural weight of 7½ per cent.

Another factor influencing the problem is the power of the vessel. In a highly powered vessel a small reduction in the power will represent an appreciable reduction in the fuel cost per annum. Again, where the machinery and fuel weights represent large fractions of the total displacement it is clear that any reductions in these will result in appreciable further reductions of displacement.

It will be seen that the method of using the weight saved to save fuel will favor the fast passenger-carrying vessel—for example, the cross-Channel vessel. The method is by no means restricted to the cross-Channel type, however.

Other methods of using the weight saved by the use of light alloys are to increase the radius of action of a vessel by increasing the fuel capacity for the same displacement and to increase the speed of the vessel. These methods are likely to be more applicable to the high-speed war vessel rather than to the merchant vessel. It is impossible to generalize on this aspect of the problem, and discussion of vessels of this type has been left out of the paper. It is clear, however, that there are many possibilities open to the designer, and the use of light alloys affords weight reduction which could not be achieved by other means.

In view of the economic efficiency of the arrangement employing light-alloy superstructures being so dependent on the value of the weight ratio w_s/w_a, it is evident that this ratio should be kept as low as possible. The question of the determination of minimum scantlings is, therefore, of vital importance.

Superstructures such as, for example, deck beams, have to withstand bending due to deck loading. In superstructure decks the deck loading is very uncertain, but it is fair to assume it to be the same in both the steel and the light-alloy vessel. The bending moment will then be the same in both cases, and if the same standard strength is to be maintained the section modulus of the beams should be increased in the ratio of

$$\frac{\text{ultimate strength of steel}}{\text{ultimate strength of light alloy}}$$

For a light alloy with a 16-ton per sq. in. ultimate strength compared with an average of 30 tons per sq. in. for steel, this ratio of $\frac{30}{16} = 1.875$. For different sections the increase in sectional area to obtain this increase in section modulus will vary, but, generally, it may be said that the necessary increase can be obtained with an increase of area of about 30 per

cent. Taking the weight of the light alloys as 167.5 pound per cubic foot, the weight ratio for such sectional material would be

$$\frac{1.3 \times 167.5}{489.6} = 0.445$$

Investigations have shown that if suitable light-alloy sections are developed this weight ratio can be achieved without increasing the depth of beams or stiffeners.

Concerning the tiers of superstructures above the first tier, it is suggested that the scantlings be determined so that the stresses in these parts do not exceed the standard stress for the light alloy wherever this is possible.

The second alternative in determining the scantlings of the first tier of superstructures is to take all the superstructures into account in calculating the section modulus of the section of the vessel. It is considered that the former method is the more advisable course, since it must be regarded as rather doubtful if the higher tiers of superstructures actually take the stresses forecast by the theory of bending.

It has been assumed that (a) the plating of the various decks gains no support from wood sheathing, and (b) the theory of bending can be applied to the composite structure.

Considering (a) it is evident that some increase in the resistance to buckling will be afforded by the attachment of wood sheathing to the decks. It does not, however, appear advisable to take any account of this, as it would not be easy to obtain a means of assessing the influence of this factor.

Regarding (b), it appears reasonable to assume the theory of bending to hold, although it must be admitted that this is only an approximation. Distortion of the sections will take place due to the presence of shear stresses. When dealing with superstructures which cover only a portion of the length of the vessel, distortion of the sections is bound to occur even if the shearing force on the vessel were zero. This is due to the fact that the ends of superstructures must be unstressed since they are free.

It is evident that if the best use of the alloys is to be made, as much steel as possible should be replaced by light alloys. Consequently, an attempt has been made to ascertain the limit to which one might go in applying light alloys to structural parts. In some of the vessels dealt with, therefore, not only have the superstructures above the uppermost continuous deck been made of light alloys, but the uppermost continuous deck itself, as well as the side plating connecting it to the deck below, have been replaced by the lighter material. This has proved successful and, in a number of cases, the two uppermost continuous decks have been so constructed.

Table 1 gives the principal dimensions and general particulars of four motor ships out of 12 vessels which have been investigated.

The profiles of these vessels are shown in Figures 1 to 4. The shading on the profiles indicates the extent to which light alloys have been used to replace the existing steel structure. Summaries of the results of the calculations are given in Tables 2, 3, 4 and 5.

Vessel C

This vessel is of the passenger and cargo type. The main structure extends to the upper deck and above this are a promenade deck and boat deck. Two alternatives have been worked in this case: the first with the normal structure to the upper deck and light-alloy promenade and boat decks above these, and the second with the upper deck and side shell between the upper and second decks constructed of light alloy in addition to the promenade and boat decks.

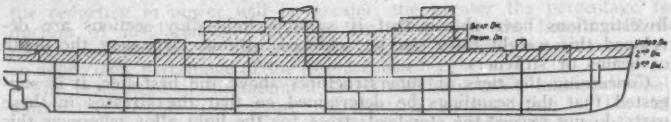


Fig. 1.—Vessel C. 450 ft. × 65 ft. × 36 ft. to freeboard (second) deck.

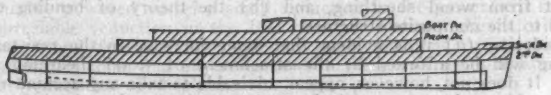


Fig. 2.—Vessel E. 360 ft. 7½ ins. × 45 ft. 11½ ins. × 24 ft. 9½ ins. to shelter deck.

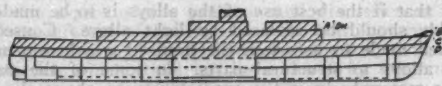


Fig. 3.—Vessel I. 350 ft. × 47 ft. × 28 ft. to C deck.

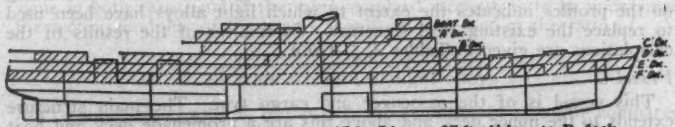


Fig. 4.—Vessel L. 501 ft. 11½ ins. × 67 ft. 7 ins. × 37 ft. 4½ ins. to D deck.

Table 1

Motor Vessel	C	E	I	L
Type	Passr. and cargo	Cross Channel	Cross Channel	Passr. and cargo liner
Length b.p. ..	450'-0"	360'-7½"	350'-0"	501'-11½"
Breadth mld. ..	65'-0"	45'-11½"	47'-0"	67'-7"
Depth mld. ..	36'-0" to freeb'd deck	24'-9½"	28'-0" to 'C' deck	37'-4½" to 'D' deck
Erections ..	Long B. and F. combined prom'de and boat decks	Prom'de and boat decks	'A' and 'B' decks	Bridge 'A' and 'B' decks
Draught	25'-6"	11'-1½"	13'-6"	25'-11½"
Approx. displ. tons	13,800	2,750	3,180	16,925
Speed (knots)	16½	22	23	17
$V/\sqrt{L}$ (on L.P.B.) ..	0.790	1.158	1.230	0.759
Approx. b.h.p.	7,200	15,000	12,500	11,400

Table 2.

Vessel "C"	All Steel Vessel.	Composite Vessel with Light Alloy Prom. and Boat Decks.	Composite Vessel with Light Alloy Prom., Boat and Upper Decks.
Stress in upper dk. (tons per sq. in.)	*6·40	*6·40 | 14·81	*3·08 | 12·12
,, ,, second ,, ,,	*4·26	*4·26 | 13·09	*6·42 | 14·30
,, ,, bottom ,,	*4·79	*4·79 | 14·19	*5·46 | 14·55
,, ,, prom. dk. ,, ,,	—	— | 12·68	— | 12·82
,, ,, Boat ,, ,,	—	— | 12·76	— | 13·52
Weight of promenade dock, boat dock, deckhouses, etc.	645 tons	195 tons	195 tons
Weight of upper deck and side plating	340 ,,	340 ,,	145 ,,
Additional steel on 2nd deck	—	—	10 ,,
Total weight saved	—	250 tons	635 ,,
Reduction in height of centre of gravity of loaded ship	—	0·6 ft.	0·8 ft.
Possible reduction of beam	—	1·5 ,,	2·0 ,,
Reduction of weight due to modified dimensions	—	80 tons	105 tons
Total reduction of displacement	—	2·3%	3·9%
Reduction of power	—	2·1%	4·0%

* Excluding superstructures above upper deck.
† Including superstructures above upper deck.

Table 3.

Vessel "E"	All Steel Vessel.	Composite Vessel with Light Alloy Prom. and Boat Decks.	Composite Vessel with Light Alloy Prom., Boat and Shelter Decks.
Stress in prom. dk. (tons per sq. in.)	5·65	2·62	3·08
,, ,, shelter ,, ,,	3·63	5·15	1·99
,, ,, second ,, ,,	1·56	2·44	2·67
,, ,, bottom ,,	2·97	3·44	3·81
Weight of prom. and boat decks, deckhouses, etc.	165 tons	75 tons	75 tons
Weight of shelter deck and side	135 ,,	135 ,,	75 ,,
Weight saved	—	90 ,,	150 ,,
Reduction in height of centre of gravity	—	0·3 ft.	0·5 ft.
Possible reduction of beam	—	0·4 ,,	0·8 ,,
Reduction of weight due to modified dimensions	—	25 tons	35 tons
Total reduction of displacement	—	4·2%	6·7%
Reduction of power	—	5·0%	7·0%

Table 4.

Vessel "I"	All Steel Vessel.	Composite Vessel with Light Alloy "A," "B" and "C" Decks.
Stress in "C" deck	5·18 tons per sq. in.	2·85 tons per sq. in.
" " "D" "	2·76 "	5·05 "
" " bottom	3·67 "	4·35 "
Weight of "A," "B" and "C" decks, deckhouses, etc.	370 tons	164 tons
Additional steel on "D" deck	—	3 "
Weight saved	—	203 "
Reduction in height of centre of gravity	—	0·7 ft.
Possible reduction of beam	—	1·0 ft.
Reduction of weight due to modified dimensions	—	40 tons
Total reduction of displacement	—	7·6%
Reduction of Power	—	8·0%

In the first of these the design of the promenade and boat decks was comparatively simple, since it was only necessary to ensure that the maximum stress in the light-alloy portion of the structure did not exceed the standard safe value and that the thickness of the higher decks were adequate to avoid buckling in the sagging condition. To keep the weight ratio low, immediate beams can, with advantage, be introduced in these higher decks. In the second arrangement, the second deck has been increased by 0.06 in. and the scantlings of the upper deck and side arranged so that the maximum stress in the steel portion of the structure shall not exceed the maximum stress in the all-steel vessel. The resulting thickness of the light-alloy upper deck would appear to be quite adequate to resist compression without the introduction of intermediate beams in this case. The results obtained for these two alternatives are shown in Table 2.

It will be seen that reduction beam is possible due to the lowering of the center of gravity and the reduction in displacement when all the weight saving has been taken into account is about 2.3 per cent in the first case and 3.4 per cent in the second case. These reductions in displacement result respectively in decreases in power of 2.1 and 4.0 per cent respectively. In this vessel the reductions in power are of sufficient magnitude for this method of using the weight saving to be useful. Alternatively, of course, it is still possible to use the weight saved as additional cargo dead-weight if this is desired, or to use the weight saving to increase the bunker capacity, in which case, the radius of action of the vessel could be considerably increased.

Vessel E

The vessel is of the cross-Channel type, of high-speed-length ratio and low deadweight in relation to displacement. As in the case of vessel C,

Table 5.

Vessel "L"	All Steel Vessel.	Composite Vessel with Light Alloy "A," "B," "C," "D" and Boat Decks.
Stress in "C" deck	5·78 tons per sq. in.	4·05 tons per sq. in.
" " "D" "	3·98 "	3·01 "
" " "E" "	4·10 "	5·78 "
" " bottom	4·16 "	5·01 "
Weight of "A," "B," "C," "D" and boat decks and deckhouses, etc.	1,515 tons	665 tons
Additional steel on "E" deck and bottom	—	30 "
Weight saved	—	830 "
Reduction in height of centre of gravity	—	1·1 ft.
Possible reduction of beam	—	2·5 "
Reduction of weight due to modified dimensions	—	220 tons
Total reduction of displacement	—	6·1%
Reduction of power	—	7·0%

two alternatives have been worked out, one with the superstructures above the shelter deck only made of light alloy and the other with the light-alloy structure taken down to the second deck. The two alternatives are shown in Table 3. In this case, due to the small total displacement of the vessel and the relatively high structural weight in relation to this displacement, a small weight reduction represents an appreciable percentage reduction in the displacement.

The influence on the horsepower is also seen to be appreciable, namely, in the first case a reduction of 5 per cent is possible, and in the second case 7 per cent reduction is possible. It would appear that the reduction in fuel in this vessel would make the adoption of light alloys worth while. There is, of course, a possible alternative, and this is to increase the spaces available for passengers by, say, adding more deck-houses. It would be possible to do this quite easily, due to the center of gravity being lowered by the top weight being reduced.

Vessel I

This vessel has the highest speed of those investigated, the speed-length ratio being over 1.2. The vessel is of similar type to E. The C deck, which is the shelter deck, is the strength deck, and this has been replaced by a light-alloy deck. The total weight-saving on the structure is well over 50 per cent, and the reduction of the displacement is about 7½ per cent. This shows a reduction of 8 per cent of power.

The stresses in this vessel are of quite moderate amount.

The results are shown in Table 4.

Vessel L

This vessel is a passenger and cargo liner of moderate speed. As in the previous vessel, the method adopted was to make the two uppermost continuous decks of light alloy and adjust beam to give the same stability, reducing prismatic coefficient to give the reduced displacement. The saving in power represents 7 per cent of the original power.

The results are shown in Table 5.

SOME RESEARCHES IN INTERNAL-COMBUSTION PRIME MOVERS.

This article consists of excerpts from a paper read before the North East Coast Institution of Engineers and Shipbuilders by James Calderwood, as they were printed in the British Motor Ship for May 1946. It consists of a summary of work done in the development of (a) highly pressure-charged reciprocating engines exhausting to gas turbines which develop a substantial part of the total power, (b) reciprocating units in which supercharging is carried to the stage where all the useful output is developed in the exhaust gas turbine, and (c) a partially closed circuit gas turbine system.

The open cycle turbine with single combustion and with or without a recuperator is already in service, but, while it is apparently mechanically sound, the efficiency that can be obtained is comparatively low. The cycle has the further disadvantage that its efficiency falls rapidly at reduced loads and must still suffer this latter disadvantage, even if it becomes possible at increased blade temperatures and with a very large recuperator, to attain a full load efficiency approaching that of the reciprocating internal-combustion engine.

Various improvements to this simple cycle have already been discussed in technical papers and articles, and descriptions have also been published

of a turbine with a totally enclosed air cycle which appears to offer advantages for higher power installations and in improved efficiency at partial loads.

The research with which this Paper deals was started some 10 years ago by Sulzer Bros. to determine practically on commercial-scale tests the most promising lines of development and the possible field of application of exhaust gas turbine used in conjunction with reciprocating machines and of continuous combustion gas turbines. (Note.—For simplicity throughout the rest of the Paper the latter will be described as "Combustion Turbine.") The work done may be divided under three main headings:—

(a) Research on highly pressure-charged reciprocating engines exhausting to turbines which develop a substantial part of the total power.

(b) Research on reciprocating units both of the normal type and of the free piston type, in which supercharging is carried to the stage where the whole of the useful output is developed in the exhaust gas turbine. The reciprocating unit used consisting of combustion cylinders and compressors is described as a "Power Gas Producer," and the system is called "The Power Gas Process."

(c) Research on the development of a cycle for combustion turbine to give reasonably high efficiency at a moderate maximum temperature with recuperator and air heater of reasonable size. A further essential characteristic of such a turbine cycle, particularly for marine service, is a reasonably flat efficiency curve at reduced loads and the correspondingly reduced speeds of the propeller.

Before describing the results so far achieved by the research, it may

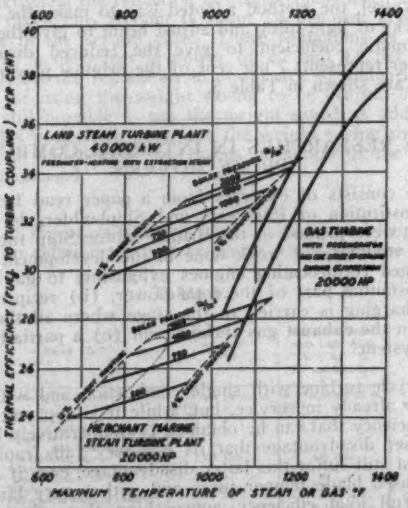


Fig. 1.—Comparison of efficiency of steam turbines with combustion turbine working on semi-closed cycle at varying maximum temperatures.

be as well to consider broadly, by means of a diagram, the efficiency that may be expected from the combustion turbine of the type developed from these researches with normal steam turbine installations. Figure 1 shows on a base of maximum turbine temperature the following thermal efficiency curves:—

1. Steam turbines and boilers, suitable for merchant ship work, 500 to 1500 pounds/square inch pressure.
2. Steam turbines using regenerative feed heating and inter-stage reheating to the maximum possible extent. Pressures 500 to 2000 pounds/square inch, as fitted in a few large power stations.
3. The marine combustion turbine of the type developed from this research.

The combustion turbine cycle shows no real advantage in efficiency over the steam turbine until temperatures in excess of 1100 degrees F. (600 degrees C.) are used, and does not compare with the efficiency of a heavy-oil reciprocating engine until the temperature is approaching 1400 degrees F. (750 degrees C.).

It may be commented here that the highly pressure-charged two-stroke engine, or the free piston compressor, exhausting to a turbine can be expected to reach efficiencies comparable with, although probably somewhat lower than, those attained with the normal compression ignition heavy-oil engine.

In comparing the turbine with the reciprocating engine, however, it must not be forgotten that, while the former should be able to use normal boiler fuel oil, the latter usually uses fuel oil of a better and more expensive grade.

It is reasonably certain that no material to-day is available which will stand up to a temperature exceeding 1200 degrees F. for the 100,000 hours' working life which is required from a marine turbine installation.

High-Pressure Charging of Two-Stroke Engines.

When this work was first started, the object in view was an increase in the specific output of normal types of two-stroke engines similar to, but greater than, that obtained with exhaust turbo pressure charging on four-stroke engines. The opposed piston type of engine was chosen for the first researches. The reasons for this choice of engine type may be of interest.

With the high b.m.e.p. that was expected, it was evident that, even for relatively high output, the cylinder diameter would be small with a correspondingly high speed of rotation. With the single piston loop scavenged engine the difficulties of scavenging and the scavenging pressure losses increase with reduced size of cylinder; the through scavenging engine, on the other hand, does not suffer so greatly from increased scavenging losses with reduced size and higher rotational speed, and these conditions are best obtained in the opposed piston type, which allows the greatest port area. With high revolution speeds and the increased maximum pressures that occur with supercharging, the resultant increased stresses are more easily catered for in the opposed piston than in the single piston engine.

High-pressure supercharging can, however, be applied to the normal single piston loop scavenged type of engine, and after the early tests on opposed piston types both single and multi-cylinder loop scavenged engines were tested with supercharging, the design suitably modified to meet the increased stresses.

A considerable part of the earlier work was described in the Sulzer Technical Review, December 31, 1941, and most of this was published in various technical journals* in this country and abroad.

* "The British Motor Ship," July, 1942 pp. 118-126.

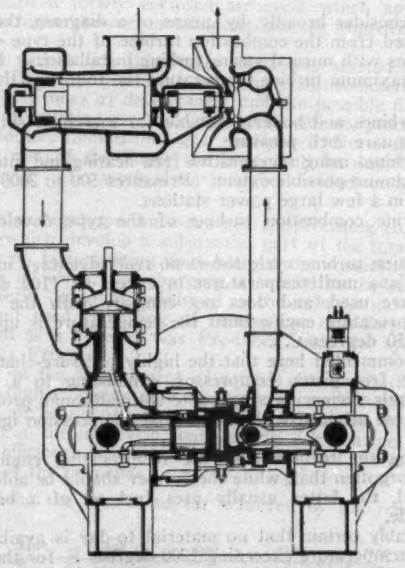


Fig. 2.—Diagram of turbo pressure-charged two-stroke engine with additional pressure charging by reciprocating compressor.

It was very evident that if the supercharged engine was to work satisfactorily, it was essential either to provide additional power to the turbo blower mechanically or electrically, to provide additional air by an engine-driven pump, or to provide all of the air by an engine-driven pump and absorb the turbine output by gearing it up to the engine.

Figures 2 and 3 illustrate diagrammatically two methods of keeping the balance of turbine power and air requirements. In Figure 2 the air compression is in two stages, the first a turbo blower driven by the exhaust turbine, the second a reciprocating pump coupled to the engine. Figure 3 shows a turbine and turbo blower geared to the engine so that at low loads power is taken from the engine to drive the blower, while at maximum loads any excess power that the turbine may develop over the blower load is available through the gearing as useful output. With this arrangement the drive between the turbo set and the engine shaft must be very flexible, a hydraulic coupling or other suitable type of flexible drive being introduced between turbine and gearing. The third arrangement mentioned above is similar to that shown in Figure 3 but the rotary compressor is omitted from the turbine shaft and replaced by a reciprocating compressor driven by the engine shaft. A further arrangement is, of course, supplementary electric drive to a separate turbo blower. Figure 4 is a diagrammatic comparison of the various arrangements which have been found to be satisfactory; each has its own advantages and drawbacks and the arrangement used must be decided according to the type of service for which the plant is required.

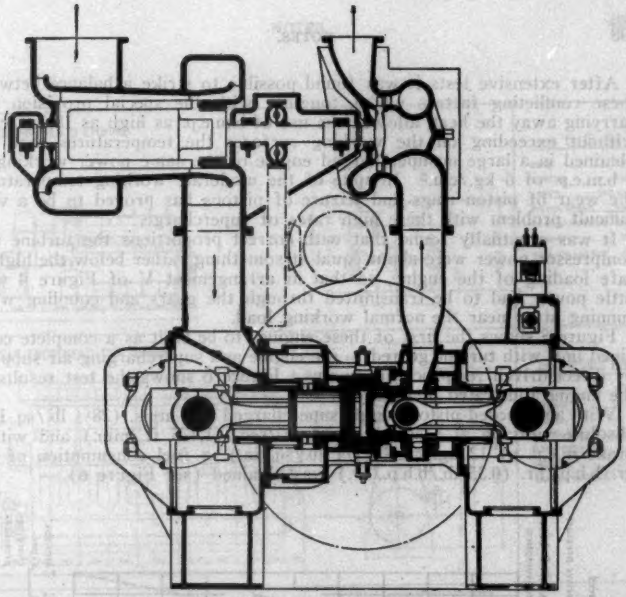
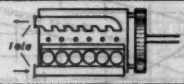
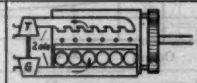
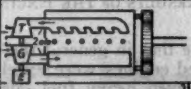
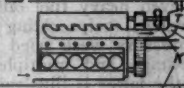


FIGURE 3.—DIAGRAM OF EXHAUST TURBO PRESSURE-CHARGED TWO-STROKE ENGINE WITHOUT RECIPROCATING COMPRESSOR BUT WITH PRESSURE CHARGER GEARED TO ENGINE.

Alternative		Arrangement	Reversibility
I	Not supercharged		fully reversible
II	Two stage supercharging		fully reversible
III	Supercharging set with additional drive		fully reversible
IV	Piston supercharging pump		limited power astern
V	Direct coupled supercharging set		not reversible

P = Scavenging pump T = Exhaust gas turbine G = Supercharging blower E = Electric motor K = Hydraulic coupling

FIGURE 4.—COMPARISON OF VARIOUS ARRANGEMENTS OF HIGH PRESSURE-CHARGED ENGINES WITH EXHAUST TURBINE.

After extensive tests it was found possible to strike a balance between these conflicting factors which, together with the special provision for carrying away the heat, allowed the use of b.m.e.p. as high as 18 kg./cm.^{2} without exceeding on the working surfaces the temperatures that are obtained in a large unsupercharged engine of the same power working at a b.m.e.p. of 6 kg./cm.^{2} In spite of the moderate working temperatures the wear of piston rings and seizure of pistons has proved to be a very difficult problem with these high rates of supercharge.

It was eventually found that with correct proportions the turbine and compressor power were about equal at something rather below the highest safe loading of the engine, so that in arrangement V of Figure 4 very little power had to be transmitted through the gears and coupling when running at or near the normal working load.

Figure 5 shows the first of these engines to be built as a complete combined unit with turbine geared to the engine and supercharging air supplied by direct driven reciprocating pumps. Figure 6 shows the test results of the engine illustrated in Figure 5.

With an opposed-piston engine supercharged to 2 atms. (28½ lb./sq. in.), absolute working at a speed of 7.5 m./sec. (1,475 ft./min.) and with a brake m.e.p. of 12 kg./cm.^{2} (171 lb./sq. in.), a fuel consumption of 158 gr./b.h.p./hr. (0.35 lb./b.h.p./hr.) was obtained (see Figure 6).

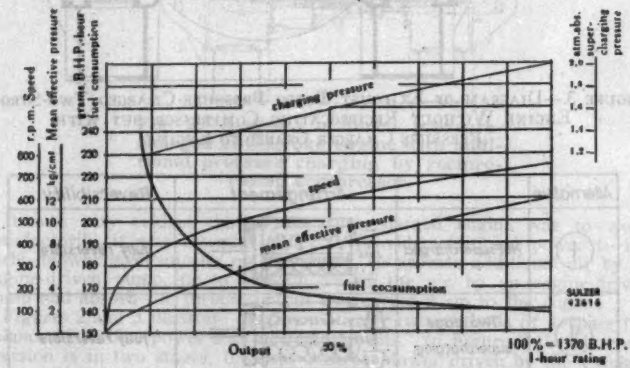


FIGURE 6.—TEST RESULTS OF THE ENGINE SHOWN IN FIGURE 5.

It is of interest to note that in general the combustion characteristics of these highly supercharged engines were excellent, and that in consequence it was possible to burn even heavy fuel oils with completely smoke-free exhaust. For supercharging, reciprocating pumps and both axial and radial flow rotary compressors were tried out with and without intermediate cooling. Single-stage and multiple-stage exhaust gas turbines were tested, and one of the latter is illustrated in Figure 7.

On the basis of these trials work was started on the construction of a 4000 b.h.p. marine engine of a design considered to be suitable for a merchant ship. This engine is now running and will be subjected to extensive shop trials. When these have reached a satisfactory conclusion it is hoped that there will be a suitable opportunity of trials in a ship. This engine, Figure 8, has six horizontally opposed piston cylinders, 320 mm. bore, 2 by 400 mm. stroke.

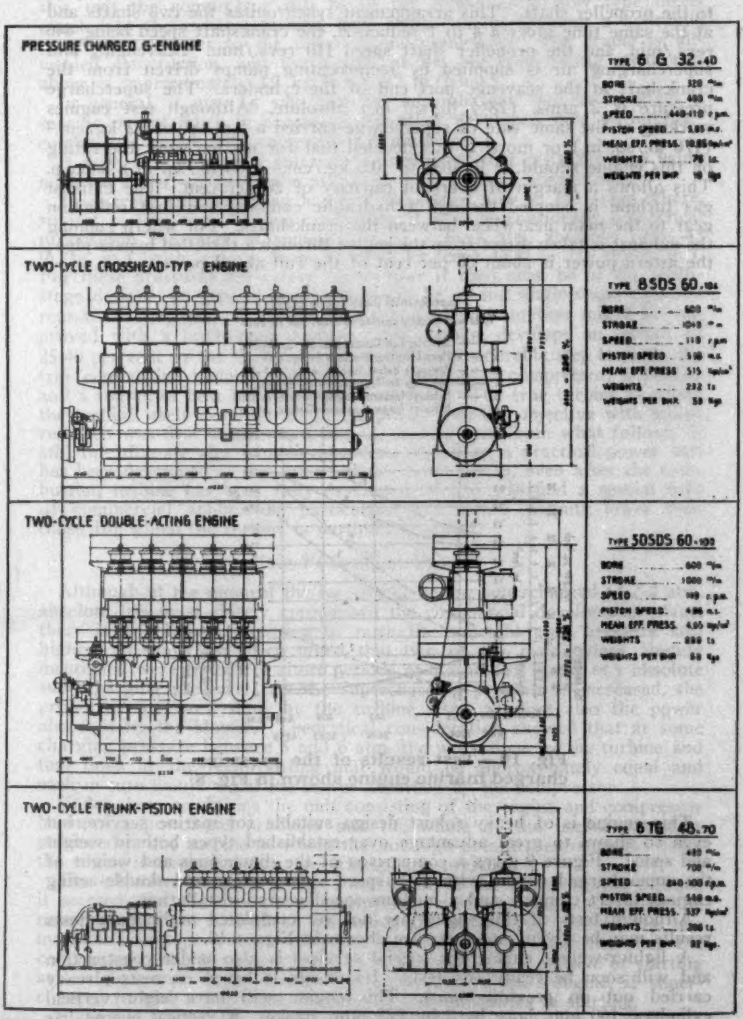


Fig. 9.—Comparison of weights and dimensions of a pressure-charged engine with a normal marine type.

The two crankshafts are geared to a common main wheel to be coupled to the propeller shaft. This arrangement synchronizes the two shafts and at the same time gives a 4 to 1 reduction, the crankshaft speed being 440 revs./min. and the propeller shaft speed 110 revs./min. Scavenging and supercharging air is supplied by reciprocating pumps driven from the crankshaft at the scavenge port end of the cylinders. The supercharge pressure is 2 atms. (28½ lb./sq. in.) absolute. Although test engines working at the same rate of supercharge carried a b.m.e.p. of 12 kg/cm.² (170 lb./sq. in.) or more, it was decided that for marine work the rating on this engine should be limited to 10.6 kg./cm.² (150 lb./sq. in.) b.m.e.p. This allows a margin of overload capacity of 20 per cent. The exhaust gas turbine is coupled through a hydraulic coupling and first reduction gear to the main gearwheel between the crankshafts. For astern running the exhaust is taken direct from the engine through a throttled bypass pipe; the astern power is about 60 per cent of the full ahead power.

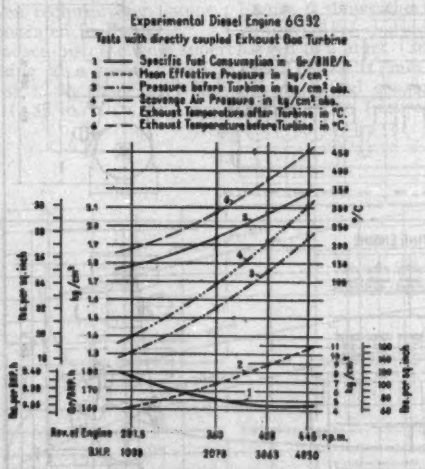

Experimental Diesel Engine 6G32
Tests with directly coupled Exhaust Gas Turbine
1 —— Specific Fuel Consumption in Gr./BHP/h.
2 ---- Mean Effective Pressure in kg/cm²
3 -·-· Pressure before Turbine in kg/cm² abs.
4 —— Scavenge Air Pressure in kg/cm² abs.
5 —— Exhaust Temperature after Turbine in °C.
6 — — Exhaust Temperature before Turbine in °C.
°C
kg/cm²
Rev. of Engine 221.5 363 439 445 r.p.m.
B.H.P. 1090 2070 3043 4050

Fig. 10.—Test results of the pressure-charged marine engine shown in Fig. 8.

This engine is of heavy robust design suitable for marine service, but even so shows to great advantage over established types both in weight and space. Figure 9 gives a comparison of the dimensions and weight of the supercharged engine with slow-speed single-acting and double-acting engines direct coupled, and a medium-speed geared installation.

Although tests of this engine are not yet completed preliminary tests results may be given, and these are shown in Figure 10.

A lighter-weight engine for special services is also under construction and will soon be ready for tests. Its design is based on tests already carried out on previous units. This engine will have eight vertical cylinders, 160 mm. bore by 2 by 225 mm. stroke. A vertical engine has been chosen in this instance. It is designed to work with a supercharge pressure of 2.5 kg./cm.² absolute, and to develop a continuous output of 2500 b.h.p. at 1000 revs./min., with a piston speed of 7.5 m.sec. (1,475 ft./min.) and a b.m.e.p. of 12.3 kg./cm.² (175 lb./sq. in). The one-hour

rating for this engine will be 2850 h.p. at a b.m.e.p. of 14 kg./cm.^{2}. In this unit the compressor will be of the rotary axial flow type direct coupled to the exhaust turbine, both being coupled through a hydraulic coupling and gears to the lower engine crankshaft. The frame is all-welded construction, and the weight at the one-hour rating mentioned above is approximately 3.2 kg./b.h.p. (7 lb./b.h.p.).

In general, it may be said that the supercharged two-stroke gives a specific output much in excess of any other developed type of internal-combustion engine with compression ignition.

It may, as a matter of interest, be mentioned that tests are also being made on a four-stroke engine at similar high rates of supercharge.

Two-stroke supercharging has been developed now to the stage where, subject to long-term service experience, it may be considered a practical proposition for rates of supercharge of 2 to 3 atm. absolute (28½-43 lb./sq. in.), with b.m.e.p. from 12 to 15 kg./cm.^{2} (170 to 215 lb./sq. in.). For these pressures the rotary compressor if used must be of the multi-stage design. In general the turbine will be of the single-stage type for reason of simplicity of design, although fuel consumption might be improved with a multi-stage turbine. The turbine develops an output of 25-40 per cent of the useful power, and is a considerable step towards the true combustion turbine, consisting essentially of a compressor, a turbine and a source of heat between these two units. The true turbine in which the turbine itself develops all of the power was the objective with which research was first inaugurated, and, as will be seen from what follows, is still the ultimate aim. In the meantime, however, a practical power unit has been developed at this intermediate, stage, which, even after the combustion turbine has been fully developed, should still find a special field of commercial application, particularly for power outputs lower than those for which the turbine is particularly suited.

The Power Gas Process.

Although at the moment the two-stroke engine supercharged to 2-3 atm. absolute has most closely approached the commercial development stage, there is an obvious incentive to raise the supercharging pressure still higher. It may have been noted that two of the test engines already mentioned were tested for short periods at 6 atm. (85 lb./sq. in.) absolute supercharging pressure. As the supercharging pressure is increased, the proportion of work done by the turbine rises, as does also the power absorbed by the blower. Theoretical consideration showed that at some charging pressure between 5 and 6 atm. the work done by the turbine and that done by the reciprocating unit would be approximately equal and each in turn would equal the power absorbed by the compressor.

Under these conditions the unit consisting of the engine and compressor becomes a power-gas producer and the whole of the useful output is produced in the turbine in which the hot high-pressure exhaust gas from the engine is expanded down to atmospheric pressure.

The intention being to produce the whole of the power in the turbine, it seemed that the free-piston compressor unit was likely to prove the most satisfactory method of producing the power gas. It has the one marked advantage over a reciprocating unit with crankshafts that the compression ratio is automatically variable, so that it is capable of starting at low pressures in the cylinder, whereas a crankshaft engine, if supercharged to such a high rate, involves severe difficulties in starting.

Figure 11 shows the design of the free-piston power-gas compressor.

Tests were first carried out on the power-gas process without a turbine, arrangement being made to exhaust against a back pressure. The first test was made on a single-cylinder crankshaft unit of 140 mm. bore. This was run at a rating corresponding to a b.m.e.p. of 18 kg./cm.^{2} (255 lb./sq.

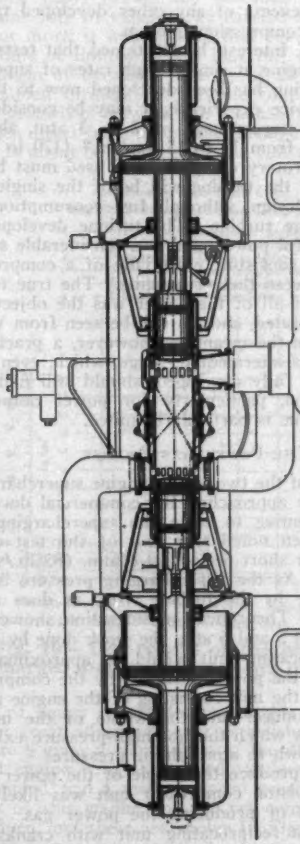


Fig. 11.—Cross section through free-piston compressor used for power-gas process.

in). This corresponds to approximately three times the specific output of a normal unsupercharged two-stroke engine. This was followed by tests on a single-cylinder free-piston power-gas producer built on a basis of the information obtained on the above-mentioned unit.

The first free-piston unit had a combustion cylinder 250 mm. bore with a stroke of 2 by 550 mm. at full load (the stroke varies somewhat according to the load). This gave a power-gas production equivalent to an output of 475 b.h.p. at the turbine. The free-piston unit ran at 280 cycles per minute. The power gas supplied was at a pressure of 5 atm. absolute and at a temperature of 500 degrees C.

As already mentioned, no turbine was fitted, but based on a turbine efficiency of 85 per cent, the results indicated that the fuel consumption was equivalent to 172 gr./b.h.p./h. (0.38 lb./b.h.p./h.). This unit was under test for a considerable period, during which experience was gained for the design of bigger units.

As a result of these tests it seemed that it would be advantageous to arrange for a certain amount of pre-compression of the air before delivery to the compressor inlet of the free-piston unit.

The revised cycle is shown in Figure 12. (This illustrates the plant that has been built with three free-piston compressors exhausting to the turbines.)

The next step in the development was the construction of a free-piston power-gas producer 400 mm. cylinder bore, 2 by 610 mm. stroke with a

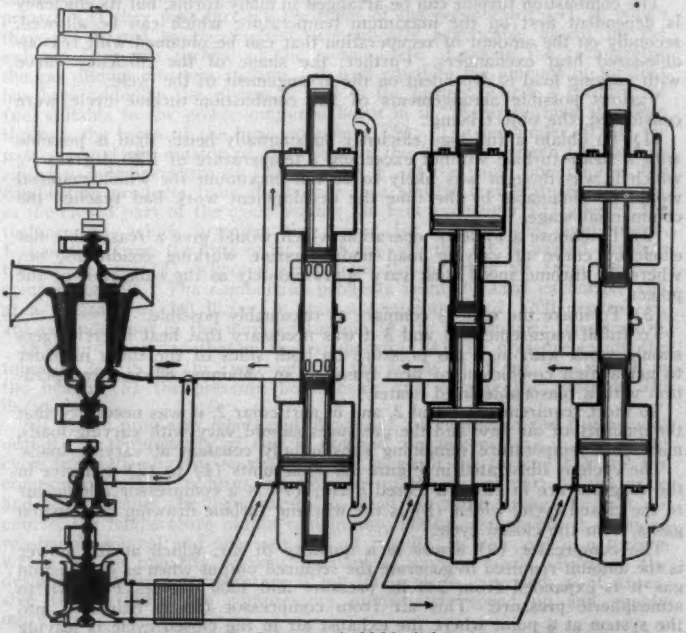


Fig. 12.—Diagrammatic layout of 6000 b.h.p. free-piston power-gas cycle turbine with exhaust turbo driven precompressor.

pre-compressor delivering air to the reciprocating compressor inlet at 1.8 atm. absolute pressure. This unit, at a speed of 350 cycles per min., gave a power-gas output equivalent to over 2000 Hp. at the turbine.

As the result of satisfactory tests on this single unit, work was put in hand on a complete power-gas plant consisting of three units similar to the above exhausting to a power-gas turbine of over 6000 Hp. (this may be increased with a higher degree of pre-compression), and also to the pre-compressor turbine. This plant was completed some time ago, and the tests made on it have proved extremely useful in the general development scheme towards the true combustion turbine.

Figure 13 shows the three power-gas free-piston compressor, whilst Figure 14 shows the turbine.

The Combustion Turbine.

The size of the reciprocating unit has been progressively decreasing throughout this series of researches, whereas the part taken by the turbine and the rotary compressor in the general scheme has been gradually increased. As regards the actual working parts, it is evident that the smallest, lightest and most convenient arrangement is likely to be the true turbine. For this reason the development of a combustion turbine without any reciprocating unit proceeded in parallel with the work which has already been described, the research on both lines being to a large extent interdependent.

The combustion turbine can be arranged in many forms, but its efficiency is dependent first on the maximum temperature which can be allowed, secondly on the amount of recuperation that can be obtained with reasonable-sized heat exchangers. Further, the shape of the efficiency curve with varying load is dependent on the arrangement of the cycle.

Various possible arrangements of the combustion turbine cycle were considered, the object being:

(1) To obtain a full-load efficiency substantially better than is possible with a steam turbine without exceeding a temperature of 1200 degrees F., which it was thought was likely to be the maximum for which material would be obtainable by the time the development work had reached the commercial stage.

(2) To choose a cycle of operation which would give a reasonable flat efficiency curve at varying load under marine working conditions, i.e., where the turbine speed must vary approximately as the cube root of the power.

(3) To make the unit as compact as reasonably possible.

To fulfill requirements 1 and 3 it was necessary that heat interchangers should work with high gas pressure on both sides of the tubes in order to get a high co-efficient of heat transfer, so obtaining efficient recuperation with a reasonable-sized heater.

To meet requirements 1 and 2, and in particular 2, it was necessary that the quantity of air flow and the pressures should vary with varying loads, maximum temperature remaining substantially constant at varying loads.

The cycle is illustrated in Figure 15. The units (1) to (7) inclusive in the diagram are in effect a closed cycle; (9) is a compressor adding air to the closed cycle, whilst (8) is the working turbine drawing combustion gases from the closed cycle.

The compressor (9) draws in a quantity of air, which at full power is the amount required to generate the required output when as combustion gas it is expanded from 240 lb. pressure and 1200 degrees F. down to atmospheric pressure. This air from compressor (9) is delivered into the system at a point where the exhaust air in the closed cycle is leaving the recuperator at 60 lb./sq. in. pressure. The freshly added air and the exhaust air mixed are re-cooled in the cooler (7), compressed in the

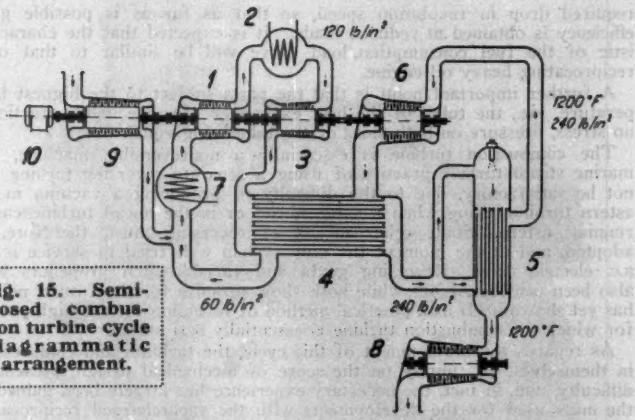


Fig. 15. — Semi-closed combustion turbine cycle diagrammatic arrangement.

compressor (1) to 120 lb./sq. in., re-cooled in the cooler (2), and finally compressed in the compressor (3) to 240 lb./sq. in. Leaving the compressor (3) they pass through the tubes of the recuperator (4), in which they are heated to the highest economically practicable extent by the exhaust from the turbine of the closed cycle. Leaving the recuperator the gas divides into two streams. A part equal to the amount of air that has been added to the system is lead to the burner, where a quantity of fuel suitable to the power output is burnt in it. After burning it passes through the tubes of the heat exchanger (5). The remainder of the air passes round the outside of the tubes of the heat exchanger (5), and is raised to a temperature of 1200 degrees F., at the same time cooling the combustion products from the burner to a similar temperature. The air in the closed part of the cycle leaving the heat exchanger (5) goes to the turbine (6), which provides the power for driving the compressors. Exhausting from the turbine at 60 lb./sq. in., the air is passed through the recuperator (4), where it again joins the incoming air from the pre-compressor (9). The combustion products from the heat exchanger (5) at a pressure of 240 lb./sq. in. and a temperature of 1200 degrees F., are expanded out in the working turbine (8) to atmospheric temperature.

It should be noted that in the recuperator (4) the pressure inside the tubes is 240 lb./sq. in., and outside the tubes 60 lb./sq. in., whilst in the heater (5) the pressure both inside and outside the tubes is 240 lb./sq. in.

All of the pressures mentioned above are, of course, at the full normal output. If the quantity of fuel is reduced, the temperature in the closed cycle first falls slightly, so reducing the speed of the turbine (6) and the compressors. This reduces the pressure in the closed part of the cycle and re-establishes the temperature to about the same figure. In fact, of course, the temperature cannot remain absolutely constant, but it is under reasonable control and does not fall off rapidly, as it would in a turbine where the air quantity remains constant at varying loads. Further, the designed maximum temperature is not likely to be exceeded, as if excessive fuel is burnt the compressors immediately speed up and supply more air.

It will be appreciated that this cycle is particularly suitable for marine work, the natural drop in pressure with reduced load corresponding to the

required drop in revolution speed, so that as far as is possible good efficiency is obtained at reduced loads. It is expected that the characteristic of the fuel consumption/load curve will be similar to that of a reciprocating heavy oil engine.

A further important point is that the parts subject to the highest temperature, viz., the tubes of the heat exchanger (5), are under practically no stress, pressure on both sides of the tube being equal.

The combustion turbine is essentially a nonreversible machine, and marine steam turbine practice of using a separate reversing turbine will not be satisfactory, due to the difficulty of producing a vacuum in the astern turbine casing when running ahead or in the ahead turbine casing running astern. Some other means of reversing must, therefore, be adopted, and at the moment the only system well tried in service is the a.c. electric drive. Reversing gears and variable-pitch propellers have also been considered, but while both show promise for the future, neither has yet shown itself as a practical method of reversing for the high powers for which the combustion turbine is essentially best suited.

As regards the development of this cycle, the turbines and compressors in themselves, i.e., purely on the score of mechanical design, present no difficulty, and, in fact, the necessary experience has largely been gained on the units used for the developments with the supercharged reciprocating engines and with the power-gas process. The main research here had to be on materials to withstand the high temperatures and on the aerodynamic efficiency of blading for the turbine and for the compressors. This was largely a matter of laboratory research. On the practical side it was felt better that the various units should be built and tested separately, so that they could be eventually combined into a complete power unit. In this respect, of course, the combustion turbine is somewhat analogous to a steam turbine, and in the particular cycle chosen the combustion chamber and heat exchanger (5) are analogous to the boiler, recuperator (4), together with the coolers (2) and (7) take the place of the feed heater and condenser of a steam plant, and the turbine and compressor, of course, replace the steam turbine, although the combustion turbine is divided into separate units of power turbine and compressor turbine.

For starting up the plant the compressor is first driven up to a moderate speed by an electric motor; item 10 in Figure 15.

As mentioned, the combined unit working on the semi-closed cycle has not yet been tested as a complete plant, but a test turbine and its combustion chamber are shown in Figure 16; Figure 17 shows the rotor of this turbine, and Figure 18 illustrates a section of the blading after the turbine had been in service.

This laboratory work in conjunction with the full-scale tests on combustion turbines and the various parts of the equipment required for the cycle shown in Figure 15, has brought the development to the stage where it can be reliably predicted that on the combined plant the efficiency will fall within the limits of the combustion turbine efficiency curve shown in Figure 1. Further, it is reasonably certain that a steel can be obtained suitable for rotor and blades working continuously at 1200 degrees F. or possibly higher. In this connection it may be well to mention that many other steels that have been examined would withstand higher stresses or temperatures for some hundreds of hours but were liable to failure due to embrittlement after periods which would represent only a few months of service in a marine installation.

It is hoped that an opportunity may be available before long to try this turbine out in regular marine service as it is realized that only service in a ship at sea can finally prove its suitability for marine use. In the meantime, work is proceeding on the construction of a comparatively

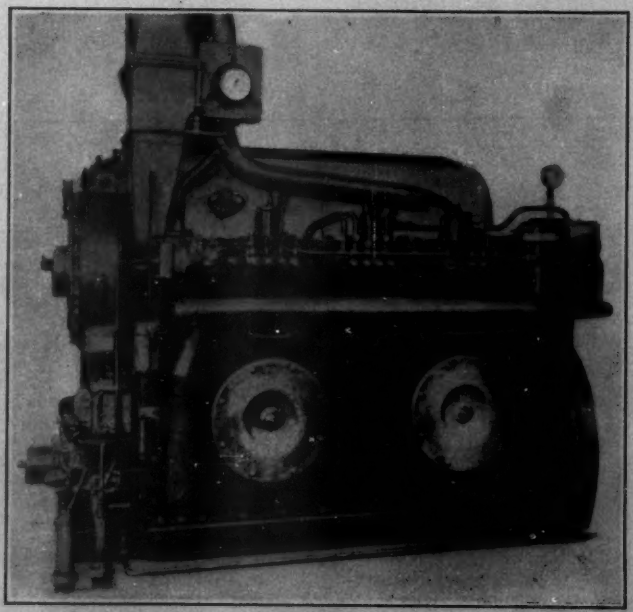


FIGURE 5.—THE FIRST HIGH PRESSURE-CHARGED TEST UNIT IN WHICH THE EXHAUST TURBINE WAS GEARED TO THE ENGINE. SUPERCHARGE PRESSURE 2 ATM. ABSOLUTE, CONTINUOUS OUTPUT 1,200 B.H.P. AT 750 REV./MIN. WITH A B.M.E.P. 12 KG./SQ. CM. (170 LB./SQ. IN.).

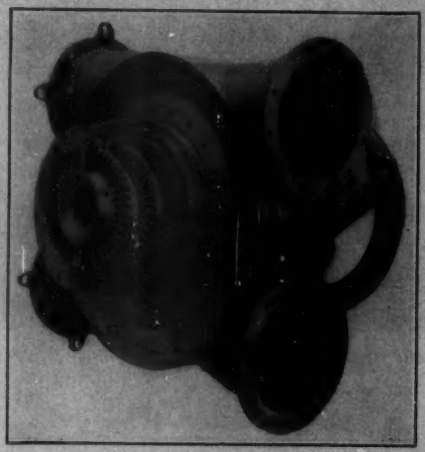


FIGURE 7.—HIGH-PRESSURE EXHAUST GAS TURBINE USED WITH 1500 B.H.P. ENGINE SUPERCHARGED TO 2 ATM. ABSOLUTE BUT DESIGNED TO WORK FOR TEST PURPOSES UP TO A MAXIMUM PRESSURE OF 6 ATM. ABSOLUTE.

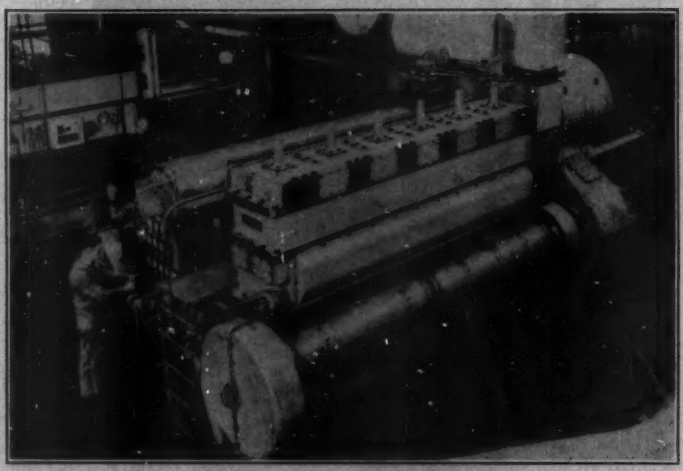


FIGURE 8.—MARINE PROPELLING ENGINE DEVELOPED FROM THE HIGH-PRESSURE PRESSURE-CHARGING TESTS GIVING AN OUTPUT OF 4000 B.H.P. AT 440 REVS./MIN. GEARED TO 110 REV./MIN. ON THE PROPELLER SHAFT.

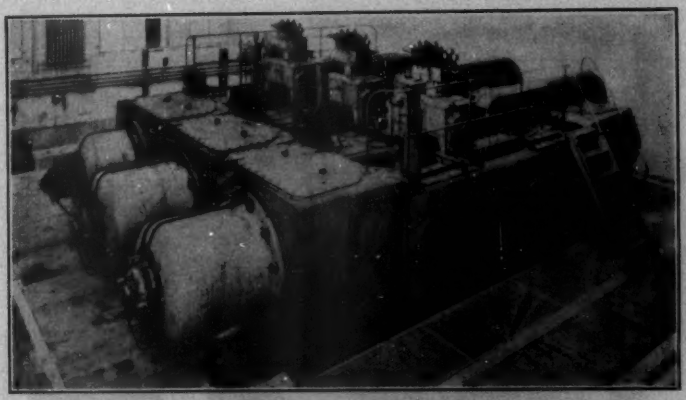


FIGURE 13.—THREE CYLINDER FREE PISTON COMPRESSOR FOR 6000 HP. TEST UNIT.

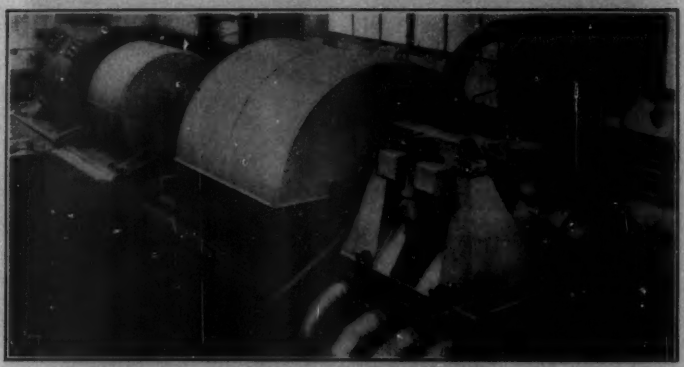


FIGURE 14.—POWER TURBINE AND PRE-COMPRESSOR UNIT FOR 6000 HP. POWER GAS PLANT.

FIGURE 16.—EXPERIMENTAL COMBUSTION TURBINE ON TEST BED.

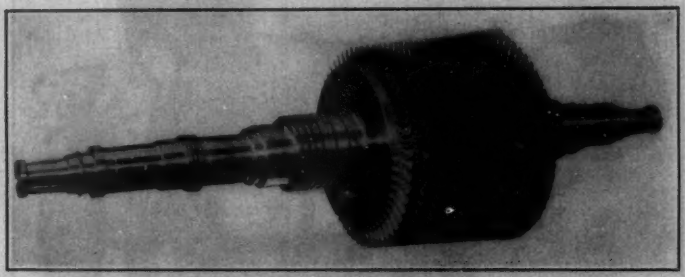


FIGURE 17.—ROTOR FOR EXPERIMENTAL COMBUSTION TURBINE.

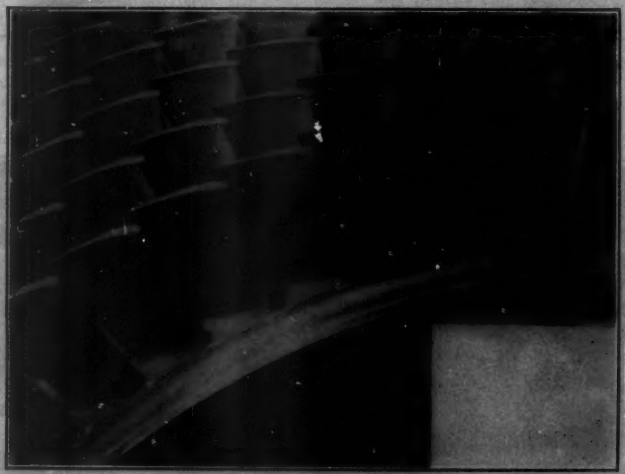


FIGURE 18.—SECTION OF BLADING FOR EXPERIMENTAL COMBUSTION TURBINE.

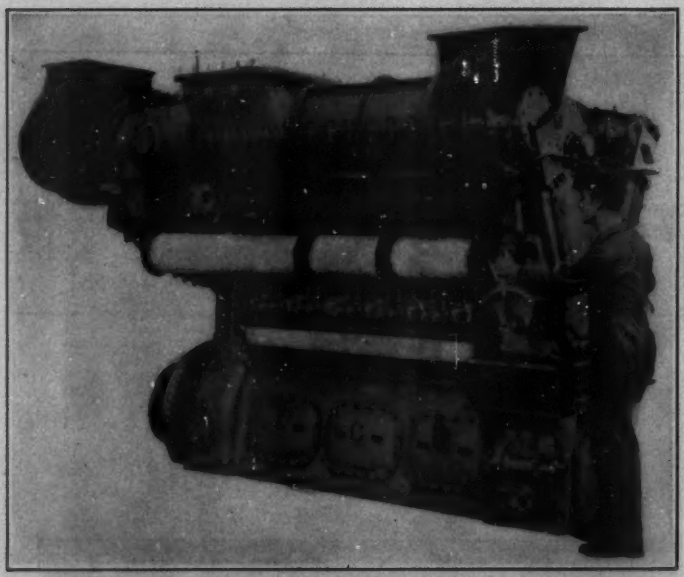


FIGURE 19—EXPERIMENTAL SIX-CYLINDER TWO-SHAFT ENGINE SUPER-CHARGED TO 2 ATM. ABSOLUTE, DEVELOPING 1500 B.H.P. CONTINUOUSLY AT 850 REVS./MIN.

FIGURE 21.—EXPERIMENTAL FREE-PISTON COMPRESSOR, 2000 HP. 400 MM. DIA.

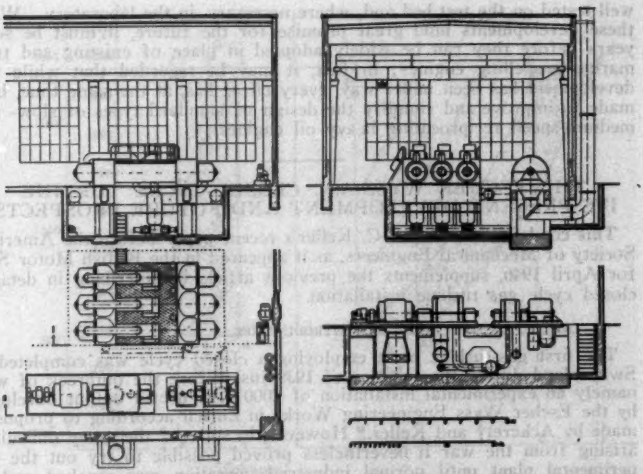


FIGURE 20.—LAYOUT OF 6000 B.H.P. POWER-GAS TEST PLANT WITH THREE FREE PISTON COMPRESSORS, POWER TURBINE AND PRE-COMPRESSOR SET DRIVEN FROM THE EXHAUST.

large combustion turbine complete with its necessary equipment and it is hoped that this will be ready for tests before the end of this year.

CONCLUSION.

To summarize the work that has been done: It has been shown that very high rates of pressure charging can be carried with safety on two-stroke engines coupled to exhaust gas turbines, and as a result prime movers of very compact size and low weight have been developed. These should, after service tests, provide a reliable and economic power unit for moderate powers, i.e., 1500 to 5000 b.h.p.

The power gas process with free piston power gas generator and with the exhaust turbine developing the useful work has been thoroughly tried out with very good results. It has not, however, been found to have such marked advantages as to be likely to hold its own in competition with the combustion turbine, in view of the rapid development and future promise of the latter. The power gas turbine is, therefore, a type of plant only likely to come into use to a limited extent for any special application for which its characteristics are specially suited. It has, however, served as a useful step in the study of turbines working with gas at high temperatures and relatively high pressure.

A combustion turbine has been developed with a cycle particularly suited to marine requirements and offering the immediate possibility of an efficiency of at least 32 per cent (0.45 lb./B.H.P./h. of oil) combined with a very flat consumption/load characteristic curve. This turbine is primarily suited for powers of 6000 b.h.p. or higher on each shaft, and so can be considered as complementary to rather than competing with the highly pressure charged two-stroke engine.

It is not for a moment suggested that these new developments can immediately be applied universally for marine propulsion. All have been

well tested on the test bed and, where necessary, in the laboratory. While these developments hold great promise for the future, it must be some years before they can be widely adopted in place of existing and tried marine propelling engines; in fact, it may be recorded that while this development has been under way, every effort has, at the same time, been made to improve and simplify the design of standard types of slow- and medium-speed reciprocating heavy oil engines.

THE ESCHER WYSS-A.K. CLOSED-CYCLE TURBINE ITS PRESENT DEVELOPMENT AND FUTURE PROSPECTS.

This condensation of Dr. C. Keller's recent paper before the American Society of Mechanical Engineers, as it appeared in the British Motor Ship for April 1946, supplements the previous article in describing in detail a closed cycle gas turbine installation.

I. Introduction.

The first gas-turbine plant employing a closed cycle was completed in Switzerland during the summer of 1939 just before the outbreak of war, namely an experimental installation of 2000 Kw. useful output developed by the Escher Wyss Engineering Works in Zurich according to proposals made by Ackeret† and Keller.* However, in spite of the many difficulties arising from the war it nevertheless proved possible to try out the experimental plant until normal industrial operation was reached and to investigate all its components. About a year ago Prof. H. Quiby (the successor of Prof. Stodola at the Swiss Federal Institute of Technology in Zurich) carried out exhaustive, official performance trials on the new plant. A report on these trials was published in June, 1945, in the "Revue Polytechnique Suisse." These official trials represent the termination of the first phase of internal scientific development and the results obtained have justified in every respect both the theoretical and practical expectations. Projects embodying such closed-circuit plant for power generation or ship propulsion can now be realized, on the basis of the preliminary studies extending over a number of years, without unwarrantable technical risks being involved. The questions that arise in this connection and the constructional solutions which we consider suitable from the technical point of view will be mainly dealt with in this paper.

The present paper refers to studies and designs, so far not published, for closed-circuit units which could now be realized from the technical point of view. Since the research work and the whole field for such installations is very extensive it is, within the framework of the present paper, only possible to discuss the principal ideas on the basis of examples.

II. Summary of the Theoretical and Physical Basis of the Closed-Circuit and its Particular Features.

As in the case of all other gas-turbine processes, it is our endeavor to approach as closely as possible the thermal efficiency of the ideal process for thermal prime movers, namely the Carnot process, and furthermore with means which are simple in practice and at the same time economical. The closed gas cycle offers favorable possibilities for realizing this aim.

In the case of air or other technical gases the Carnot process proper (Figure 1) is accompanied by considerable practical drawbacks, because for attaining the high initial temperatures T_1, which modern steels are capable of withstanding, very high pressure ratios P_1/P_2 from 200 to 300

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† Professor of Aerodynamics and Flow Mechanics, Swiss Federal Institute of Technology, Zurich.

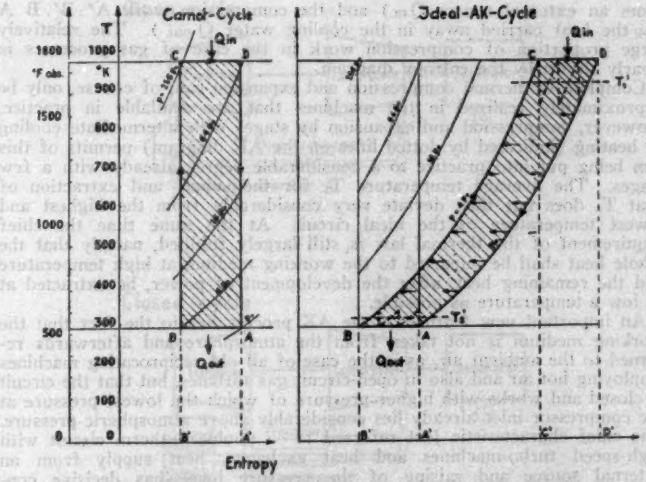

Fig. 1. Fig. 2.

Entropy diagrams of the Carnot cycle (1) and the AK cycle (2).

have to be dealt with, especially during the adiabatic compression, which is very difficult to realize in turbo-machines.

The AK process endeavors to bring about a cycle, the so-called double-isotherm cycle, which is thermally equivalent to the Carnot cycle for gases. Figure 2 illustrates this cycle in comparison to the Carnot cycle proper. The AK process employs only small pressure ratios between A and B for isothermal compression of the air. Further adiabatic compression between B-C, according to Carnot, is intentionally dispensed with and replaced by an internal exchange of heat at constant final pressure of the preceding isothermal compression. The supply of heat from an external source by the combustion of fuel, as in the Carnot process, takes place exclusively along the isotherm C.-D. After this expansion with simultaneous development of power, the heat is reimparted to the gas along B-C by internal heat exchange in the circuit itself, whereby the pressure remains constant. This double-isotherm circuit has exactly the same theoretical efficiency as the Carnot cycle and is consequently only dependent on the temperatures

$$E = \frac{T_1 - T_2}{T_1} \text{ (absolute temperatures).}$$

But the high pressure ratio, which is such a drawback, is entirely avoided; it can be reduced to a small fraction of the above value and one is not bound to a given relationship $P_{max.} : P_{min.}$ for attaining the maximum temperature T_1.

The hatched surfaces ABCD in the entropy diagrams, Figures 1 and 2, illustrate the work obtained for each unit weight of gas (air) for the Carnot circuit and for the double-isotherm circuit. This work is the difference between the turbine output D′ C′ C D (= the heat supplied

from an external source Q_m) and the compression work A′ B′ B A (= the heat carried away in the cooling water Q_{out}). The relatively large proportion of compression work in the case of gas processes is clearly shown by the entropy diagram.

Complete isothermal compression and expansion can, of course, only be approximately realized in the machines that are available in practice. However, compression and expansion by stages with intermediate cooling or heating (indicated by dotted lines on the AK diagram) permits of this aim being put into practice to a considerable degree already with a few stages. The average temperature T_1 for the supply and extraction of heat T_2 does not then deviate very considerably from the highest and lowest temperature of the ideal circuit. At the same time the chief requirement of the thermal law is still largely fulfilled, namely that the whole heat shall be imparted to the working medium at high temperature and the remaining heat, after the development of power, be extracted at as low a temperature as possible.

An important new feature of the AK process lies in the fact that the working medium is not taken from the atmosphere and afterwards returned to the ambient air, as in the case of all old reciprocating machines employing hot air and also in open-circuit gas turbines, but that the circuit is closed and works with higher pressure of which the lowest pressure at the compressor inlet already lies considerably above atmospheric pressure. The chief characteristic just referred to—a double-isotherm circuit with high-speed turbo-machines and heat exchange, heat supply from an external source and raising of the pressure level—has decisive consequences for the realization in practice, which shall now be referred to.

To illustrate the fundamental difference between the method of operation of the ordinary combustion turbine and the closed circuit of the AK plant, simplified layouts for these different installations are compared with one another in Figures 3 and 4. In place of the combustion chamber one has for the closed-circuit an air heater that is heated from an external source and corresponds to the boiler of a steam-turbine plant. In comparison to the open-combustion turbine which discharges its waste air to the open, the only additional component of the AK plant is a pre-cooler which cools the working medium after it has passed through the turbine and heat exchanger, to as low a temperature as possible before being reinhaled by the compressor. The principal feature of our process and the characteristics resulting therefrom may be summarized as follows:

(*1*) *The Closed-pressure Circuit.* Soiling of runner or impeller blading as also of heat-exchanger surfaces by combustion residue or other foreign matter is completely eliminated, which provides a guarantee that the efficiency of the machine and the heat transmission coefficients will remain unchanged. The working medium that is always clean permits the adoption of small cross-sections for the elements of the heat exchangers.

The system is so supercharged that the pressure at the suction branch of the compressor already lies considerably above atmospheric pressure. As a consequence of this supercharging the dimensions of all parts of the plant, both machines and heat exchangers, are considerably reduced, on the one hand, owing to the smaller specific volume of the working medium and on the other hand because of the considerably increased heat transmission coefficients at a higher pressure. Such supercharged operation permits of the unit outputs being increased almost without limit.

(*2*) *External Heating.* By separating the circuit of the working medium from that of the combustion air it becomes possible to employ any kind of solid, liquid or gaseous fuel, such as bituminous coal, lignite, oil or gas.

(*3*) *Output Regulation.* The output of the plant can be varied by

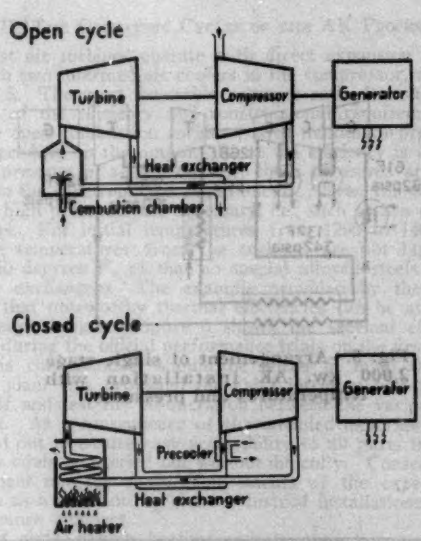

Fig. 3 (top), Fig. 4 (bottom).—Diagrams of open and closed-cycle systems.

changing the pressure level, without altering the temperatures and whilst maintaining the efficiency practically unaltered at all loads. By raising or lowering the pressure level—brought about by temporarily supplying or extracting working medium to or from the circuit—the plant can be suited to any desired part-load, simply by changing the density of its working medium. In doing this, the flow conditions in the machines, the pressure ratios, the velocities, and the angles of attack to the blades remain practically unchanged, the same being true of the internal efficiency. The machines thus always operate at exactly the same point of their pressure-volume characteristic. Consequently the efficiency of the plant is almost equally high at part-loads as at full-load, only the constant losses arising from bearing friction and heat radiation being proportionately more pronounced at part-loads. The fact that the temperatures remain unchanged at all loads is a particular advantage for the practical operation of such plant at high temperatures. No regulating valves, etc., are provided in the circuit proper, i.e., either on the machines or apparatus. The means for controlling the supply and withdrawal of air, which is stored in cold compressed-air accumulators, are united in a regulating set outside the circuit of the working medium and are traversed only by cold air.

(*4*) *The Use of Other Gases.* Other working media than air can only be adopted in the case of a closed circuit with an external supply of heat. The employment of suitable light gases, such as helium, for example, opens up the possibility of increasing the output of the plant for the same dimensions, or of further raising its efficiency as a consequence of the particular physical characteristics of such gases for special purposes (drive of transport means or aircraft).

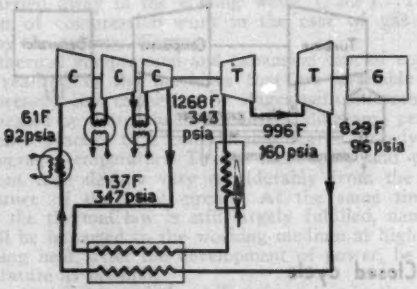

Fig. 5.—Arrangement of single-stage 2,000 kw. AK installation with temperatures and pressures.

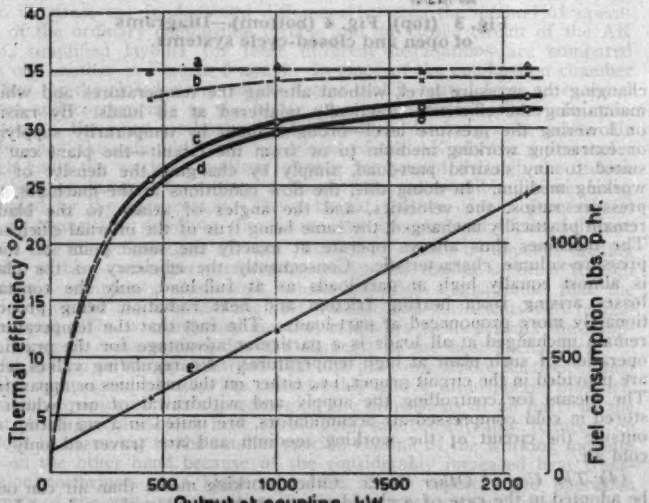

Fig. 6.—2,000 kw. efficiency curves.

a.—Efficiency without insulating and bearing losses. b.—Efficiency, without bearing losses. c.—Efficiency without auxiliaries. d.—Net efficiency, all losses included. e.—Fuel consumption.

III. The Operating Cycles of the AK Process.

The simplest air turbines operate with direct expansion in the turbine itself and with two intermediate coolers in the compressor, as may be seen from Figure 5. The most favorable pressure ratio for such plant, with consideration of the efficiency and constructional requirements, is about 3 to 4 as for open combustion turbines, with maximum pressures of 400 to 500 psi depending on the output. Since the efficiency is independent of the absolute pressure in all air circuits, these pressures are chosen only with regard to the constructional requirements. Even for the largest outputs no very high pressures are necessary, i.e., such as are encountered in steam turbines. For initial temperatures from 1200 to 1400 degrees F., the discharge temperatures from the turbines are not higher than 750 degrees to 950 degrees F., so that no special alloyed steels are necessary for the heat exchangers. The example provided by the experimental plant proves that noteworthy thermal efficiencies can be attained already with single-stage designs. Figure 6 shows the thermal efficiency which was obtained during the official performance trials on the first experimental plant. In this connection it should be borne in mind that when this experimental plant was projected the chief intention was to try out the principle itself and test the co-operation between the various components of the circuit. As a consequence of the intended experimental work the plant was laid out to ensure easy accessibility to all parts thereof, so that measurements could be carried out without difficulty. Consequently neither the arrangement nor the space requirements of the experimental plant may be taken as a criterion for later industrial installations which can be made much more compact.

Installations with double heating operate according to the diagram, Figure 7. Figure 8 is the corresponding Sankey diagram. In actual installations, maximum pressures of 400 to 600 psia with back pressures of 40 to 60 psia will be adopted for small outputs, whereas for larger outputs above 10,000 Kw., we raise the pressure up to maximum 850 psia with about 85 psia back pressure. The heat drops are in this case also so distributed that the heat exchanger can be built without requiring the use of special alloyed steels.

AK installations are quite suitable for standardization. Thus, for example, the whole range of stationary installations from 3,000-50,000 Kw. can be dealt with by a few types of machines. This standardization, which has been attempted but never realized in the case of steam turbines, will have a favorable influence on the price calculations.

1. Turbines and Compressors. Since the specific volume is reduced owing to the raised working pressure of the closed circuit, the machines are astonishingly small when compared to open-circuit combustion turbines. In addition the heat drop that has to be dealt with is much less than with steam-turbines, so that the closed-circuit turbine has not many stages.

Special attention has to be paid to the inlet and outlet losses which, as a result of the small pressure and temperature drops that are utilized, play a relatively important part. The absence of any regulating devices permits of the turbine being situated, literally speaking, immediately in the piping conducting the working medium, an arrangement with which one is familiar in the construction of hydraulic machines. It is possible, for example, to pass the working medium through a bend-shaped supply pipe to the first runner wheel without employing annular channels. The outlet can be made symmetrical and a considerable part of the kinetic energy can be recovered, for instance in spiral outlet casings as in hydraulic turbines or pumps. Such forms are also used for the axial-flow compressors. The small turbines also permit the adoption of double casing designed on the same principle as the hot-air pipings. Between the thin

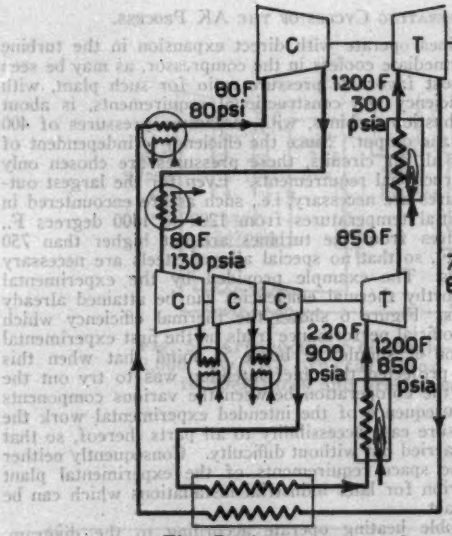

Fig. 7.—Arrangement of two-stage plant with intermediate heating. Typical data of 25,000 kw. unit.

internal shell and the external casing there is a layer of insulating material; the internal casing serves only for conducting the hot current, whilst the cold external casing takes up the pressure. The whole guide apparatus is fixed to the casing at a point where temperatures are low. In this manner the external casing is, even for high inlet temperatures, subject at the most only to the discharge temperature of the last stage (approximately 925 degrees F.). Thus, although the turbine-inlet temperature is much higher, heat-resisting steel need not be adopted for the casing but only for the small internal parts.

Similar construction principles, dictated by the latest knowledge in the field of flow technics, apply also for the compressor and for the intermediate coolers forming part of the latter.

Since relatively large quantities of air but small increases in pressure have to be dealt with, up-to-date axial-flow turbo-compressors of the multi-stage type are particularly suitable for such duty. The high speeds needed for this type of compressor lie within limits which offer good constructional conditions also for the driving turbine. As a result of these high speeds the compressor set is of small dimensions even when dealing with the largest volumes. It has been possible to raise the efficiency of the bladings above the values attainable with radial compressors. As turbine and compressor always and at all loads work at the same operating point, high-quality blading need only be developed for this one point without compromises. For these conditions the course of the pressure-volume characteristic for part loads need not be considered. For the same reason, for instance, in the case of small outputs or other gases, radial compressors can also be adopted, thus leading to fewer stages.

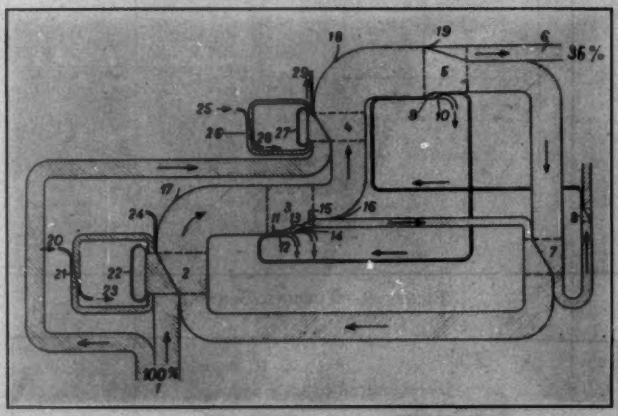

Fig. 8.—Sankey diagram.

1.—Calorific value of the fuel. 2.—High-pressure air heater. 3.—High-pressure turbine. 4.—Low-pressure air heater. 5.—Low-pressure turbine. 6.—Output at turbine coupling. 7.—Heat exchanger or recuperator. 8.—Pre-cooler. 9.—Low-pressure compressor. 10.—Low-pressure intercooler. 11.—Medium-pressure compressor I. 12.—Medium-pressure intercooler. 13.—Medium-pressure compressor II. 14.—High-pressure intercooler. 15.—High-pressure compressor. 16.—Mechanical losses of the high-pressure set. 17.—Heat losses on the high-pressure side. 18.—Heat losses on the medium pressure side. 19.—Mechanical losses of the low-pressure set. 20.—Combustion air of the high-pressure air heater. 21.—Combustion air pre-heater of the high-pressure air heater. 22.—Circulating flue gases of the high-pressure air heater. 23.—Chimney of the high-pressure air heater. 24.—Heat losses of the high-pressure air heater. 25.—Combustion air of the low-pressure air heater. 26.—Combustion air pre-heater of the low-pressure air heater. 27.—Circulating flue gases of the low-pressure air heater. 28.—Uptake of the low-pressure air heater. 29.—Heat losses of the low-pressure air heater.

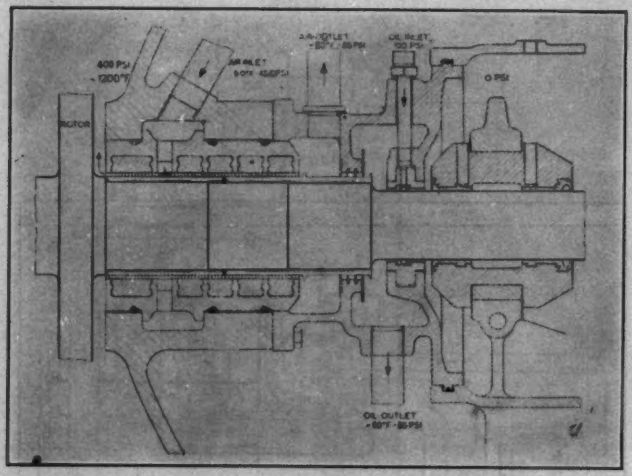

FIGURE 9.—TURBINE GLAND.

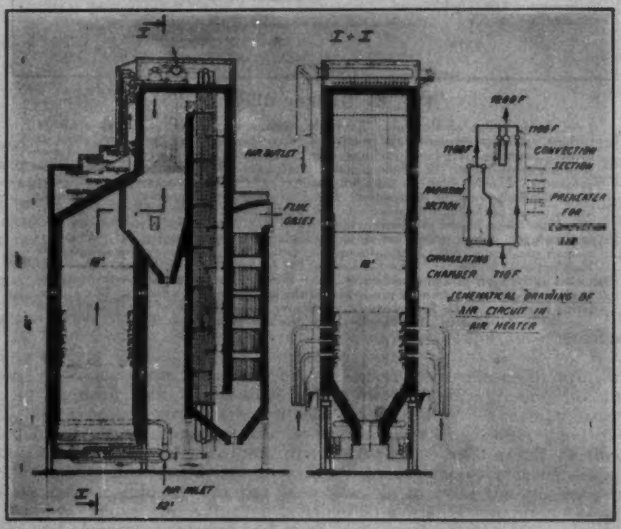

FIGURE 10.—AIR HEATER FOR COAL FIRING, WITH PULVERIZING CHAMBER FOR 12,500 KW. UNIT.

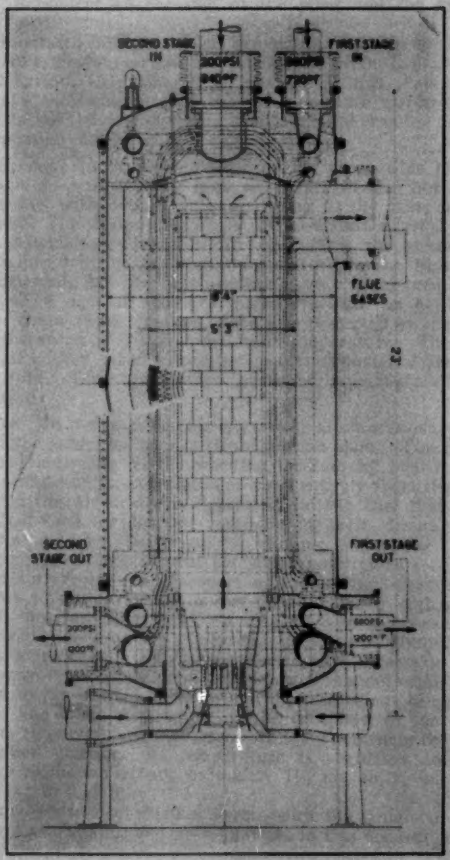

FIGURE 11.—OIL-FIRED AIR HEATER FOR 6,000 KW. SET.

The rotating shafts of the machines are sealed from the ambient air by means of labyrinth glands or a combined system of labyrinth glands with liquid sealing, dependent on the size of the plant and the kind of gas employed.

The gland illustrated in Figure 9 has proved its merits in the case of the experimental plant. Sealing air extracted from the circuit is passed through pipes to the labyrinth chambers. The pressure of this sealing air is at all loads always somewhat higher than the pressure inside the glands, corresponding to the point where it is bled from the circuit. In this way it becomes impossible for hot air to escape.

2. Hot-air Piping. In order to reduce as far as possible the quantity of metal capable of withstanding high temperatures, the hot-air pipings have been executed with double walls according to the same principle as for the turbines. The design comprises a thin-walled internal tube of a heat-resisting material serving only for conducting the stream of gas. This tube is relieved by bores from the pressure in the heat-insulating space which surrounds it. The heat-insulating space in its turn is enclosed by a thicker-walled pipe of standard material which can easily take up the pressure of the working medium, since it is protected by the insulating material and, therefore, it is not under high temperature. The necessary measures are, of course, taken to prevent insulating material from gaining access to the tube. With this design much high-quality and expensive steel can be saved.

3. Air Heater. In the aerodynamic circuit the air heater plays a similar part to that of the steam boiler in a steam-turbine plant. The heat of the fuel is imparted indirectly to the working medium by heat-transmission surfaces, the combustion gases being kept away entirely from the machines.

The design of the air heater is dependent on the fuel that has to be dealt with. Coal-fired air heaters resemble in their design up-to-date steam boilers, as may be seen from the example, Figure 10. According to the present stage of development the space requirements of coal-fired air heaters are not greater than those of up-to-date high-pressure boilers. Figure 10 shows a section through a coal-fired air heater with pulverizing chamber. This project for a 12,000-Kw. plant is very conservative as regards the combustion chamber as also the stresses and temperatures for the tube walls, since care in this connection appears necessary for a first execution. It may, however, be definitely expected that subsequent developments will lead to the heating surfaces and the dimensions being considerably reduced. The inlet temperature of the tube nest in the convection section amounts to only about 1850 degrees F. By returning the flue gases in the combustion chamber, its temperature is regulated and reduced. The tubes have diameters of approximately 1½ ins. to ¾ in., with wall thicknesses of 0.1 to 0.15 in.

It is not proposed to deal further herein with the details of coal-fired air heaters, since our studies and investigations in this connection have not been completed in all respects.

Figure 11 shows an example of an oil-fired air heater for a 6,000-Kw. plant with 600 psia and double heating. The tubes are arranged round a supercharged combustion chamber. The tube walls for heating the air in the first stage and in the second stage, 600 psia and 200 psia respectively, are united in a common heater. In the case of this project the combustion chamber is lined with refractory material and the heat is given up to the tubes mainly by convection. By raising the pressure of the combustion gas to about 45 to 70 psia and with velocities of combustion gases from 100 to 160 ft./sec., and air velocities inside the tubes from 65 to 130 ft./sec., the heating surface can be kept small. For such projects it amounts to only 0.5 sq. ft./kw. net output of the plant. The total weight of

iron in such an air heater is less than 9 lb./kw. Of this figure the proportion of alloyed steels is about 50 per cent. The tubes, which may expand in operation by about 2½ ins., can move freely in the upward direction. In order to keep the hot-air piping as short as possible, the heated air for the high-pressure turbine and low-pressure turbine is discharged below. The shell of the heater is of ordinary steel and made airtight. It can be dismantled in a number of sections, so that the tubes are easily accessible from the side and can be removed without difficulty. The shell serves at the same time as a support for the tubes.

Since the waste gases are still of high temperature (approximately 1,000 degrees F.), they are expanded in an exhaust turbine and simultaneously cooled. The exhaust turbine drives the compressor for the combustion air. In this way a preheater for the combustion air can be entirely eliminated. The supercharging set need not be particularly efficient because most of the losses are recovered in the firing. As there is no regenerator there is little danger of detrimental soiling. The design of an air heater employing blast-furnace gas or natural gas is, for the greater part, the same as for oil firing. The heating surfaces are likewise very similar.

4. Heat Exchanger (Recuperator). Unless a heat exchanger is employed it is hardly possible to increase the thermal efficiency of any kind of gas turbine plant above about 20 per cent. The quantity of heat that has to be given up by the current of gas issuing from the turbine to the

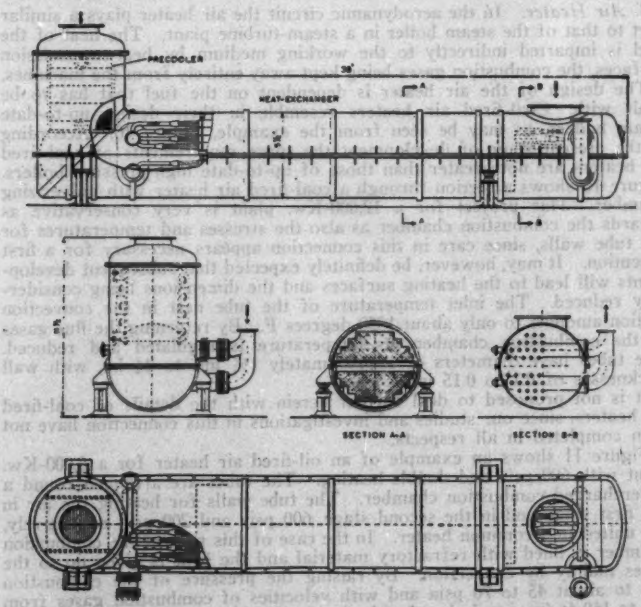

FIGURE 12.—HEAT EXCHANGER OF 6,000 KW. CLOSED-CYCLE UNIT BUILT UP OF SMALL-DIAMETER TUBES. PRECOOLER IN THE SAME SHELL.

current of gas after the compressor, at full regeneration, is of the same magnitude as the quantity of heat which in the air heater is introduced from an external source.

In principle, any kind of heat-exchanging surface (flat or tubular) and any means for conducting the flow can be adopted. However, since the plant operates under pressure, the use of simple steel tubes which can be manufactured at relatively low cost represents th given means for effecting this transmission.

Figure 12 illustrates the design of a tubular exchanger operating according to the counter-current principle and transmitting a maximum amount of heat with a minimum loss of pressure. The high-pressure air flows through the interior of the tubes and the external shell has only to withstand the lower back-pressure. The apparatus can be arranged as desired according to the available space or subdivided into two or more parts. The use of normal tubes of small diameter permit standardization of all heat-exchanger elements for the various outputs and thus to a large degree manufacture in series.

We employ tubes of only 0.15 to 0.25-in. diameter. They are spaced by special distance pieces offering little resistance to the current of air. A large number of these thin tubes is united in a tube nest. In their turn the latter are connected by a small number of collector pipes. Separate removal of each tube nest is easily possible. In the case of stationary plants this can be effected, for example, by drawing the various tube sections out of the heat exchanger in an axial direction. For marine installations the shell of the heat exchanger is split and can be easily lifted, thus giving access to the tube nests from above. The tightness of each nest can be checked separately. However, since a perfectly clean medium flows on either side of the tube walls there is no reason to fear interruptions in the operation. Furthermore, the highest temperature in the heat exchanger amounts to only about 850 degrees F., so that it is unnecessary to employ special-quality metals for the tubes.

In many cases it is advantageous to combine the LP-turbine arranged in the circuit before the heat exchanger, in the manner illustrated by Figure 13. In this way additional pressure losses are avoided and the stream of air passes direct to the tube nest. As may be seen from Figure 13, the heat exchanger, whether arranged in this or some similar manner, is an exceptionally simple apparatus that operates very reliably.

5. Governing. For raising the output, air is introduced to the circuit from a high-pressure accumulator of cold air, whilst, for reducing the output, air is withdrawn from the circuit and passed to a low-pressure accumulator. Automatic governing for an installation with rigid couplings between the machines takes place fundamentally as follows: When load is thrown off, the consequent rise in speed influences the centrifugal governor (pendulum) which causes the discharge side of the combined inlet-outlet valve to open, consequently air from the high-pressure branch of the circuit issues into the low-pressure accumulator LP. On the other hand, when load is thrown on the plant, the resulting drop in speed causes the inlet side of valve to open, as a consequence of which air from the high-pressure accumulator HP is admitted to the circuit at the same point. For small reductions in load and consequently only slight increases in speed the main valve operates only within a small range without opening either the inlet or outlet.

The test plant has worked for long periods entirely separated from the municipal network and supplying the whole works of Escher Wyss. On these occasions, the regulating governing proved, in its simplest form, to be very satisfactory.

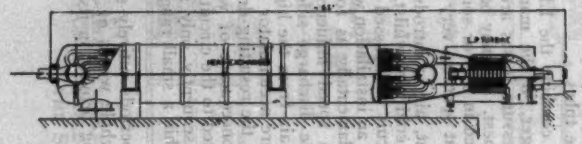

Fig. 13 (above).—Combination of heat exchanger and turbine to economize space. 25,000 kw.

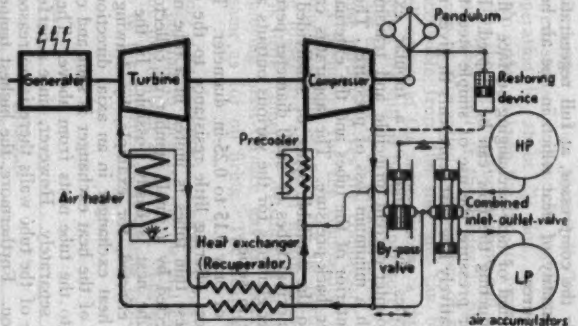

Fig. 14 (right).—Speed regulation, single-shaft unit with combination of inlet and outlet valve with by-pass valve.

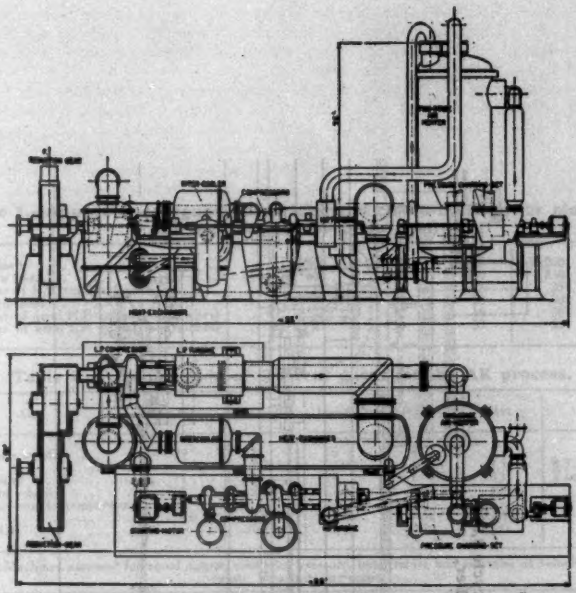

FIGURE 15.—LAYOUT OF HIGH-EFFICIENCY 8,000 S.H.P. CLOSED CYCLE UNIT FOR MARINE PROPULSION.

An arrangement of the sets in parallel is preferable for marine installations. Figure 15 shows a marine plant with oil firing for 8000 s.h.p. This plant can be used for turbo-electric drive or for propulsion in conjunction with a variable-pitch propeller. It operates with 600 psi, 1200 degrees F. before the turbine, with double heating and supercharged firing of the air heater. The combustion circuit is entirely separate from the working circuit proper, so that they do not influence one another during regulating actions. The reduced strain for the tubes in the case of supercharged firing permits the wall thicknesses to be reduced. The back-pressure amounts to 60 psi. The air heater is arranged in front of the machine set. The heat exchanger lies amidships. On the one side is the compressor set for the circuit. It is driven by the high-pressure turbine. On the same side is the charging set for the combustion chamber which receives its drive from an exhaust turbine. The low-pressure turbine is the prime mover proper. With this arrangement all parts are easily accessible and can be dismantled without difficulty since they all lie in the same plane. When the propeller speed is changed under varying loads only the speed of the low-pressure turbine is correspondingly altered. The thermal efficiency of such a marine plant, including auxiliaries, amounts at full load and 1200 to 1300 degrees F. to about $32 \div 34$ per cent., and still attains at $\frac{1}{3}$ load an efficiency of $27 \div 30$ per cent. The weight of the group in relation to output is approximately 40 lb./s.h.p.

In accordance with present progress in metallurgy, it is intended to operate AK plants at temperatures of 1200 degrees F. to 1300 degrees F.

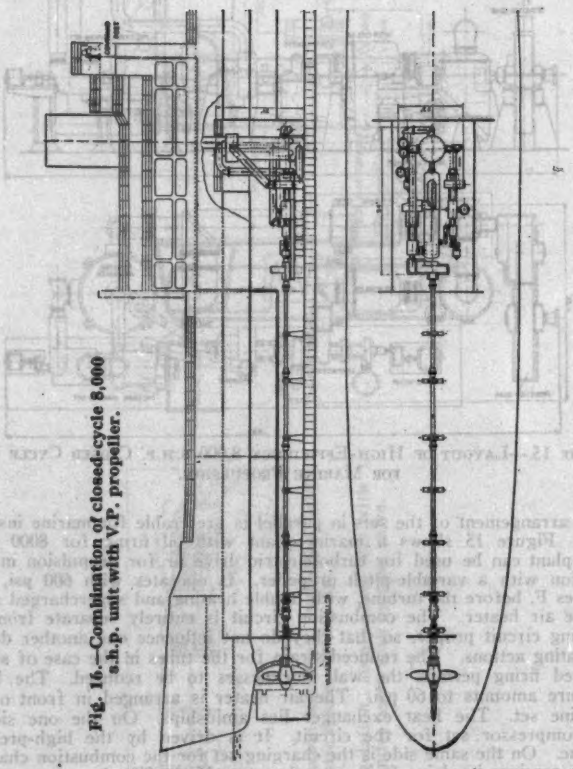

Fig. 16.—Combination of closed-cycle 8,000 s.h.p. unit with V.P. propeller.

Table 1.—Approximate figures for machine of closed-cycle power plants of different outputs (60 cycles/sec.)

Net output (kw.)	6,000	12,000	25,000	50,000	100,000
Max. pressure (p.s.i.)	600	600	850	850	850
Max. diameter of H.P. turbine (inches)	17	19	26	35	47
L.P. turbine (inches)	31	39	50	70	87
Max. diameter of axial H.P. compressor (inches) ..	10	12	16	20	27
Max. diameter of axial L.P. compressor (inches) ..	21	30	33	53	65

Table 2.—A comparison of different gases for the AK process.

Gas	Air	$He+CO_2$	$He+CO_2$	He	H_2	
Mean molecular weight	29	8	6	4	2	
Spec. heat	0.25	0.755	0.90	1.25	3.5	B.T.U./lb. °F.
Ratio of viscosity	1	1	1	1	0.5	T constant
Ratio of sound velocity	1	2.1	2.4	3.0	3.9	
Adiab. pressure ratio for temperature ratio	4.0	2.92	2.71	2.52	3.65	
Vol.-% CO_2 1.45	—	10	5	—	—	

Machines assumed for equal output, maximum pressure, temperature and triangles of velocity. const. T=const. p=const.

Number of stages (ratio)	1	2.8	3.5	4.8	13.5	(a) Const. circumferential velocity
Circumferential velocity	1	1.75	1.9	2.2	3.7	(b) Constant number of stages
Diameter (ratio)	1	0.76	0.73	0.68	0.52	
R.P.M.	1	2.30	2.6	3.3	4.1	
Heat Exchanger						
Coefficient of heat transmission ..	1	1.86	2.12	2.56	4.35	
Number of tubes	1	0.66	0.62	0.56	0.27	(ratio)
Length of tubes	1	0.82	0.76	0.70	0.85	
Surface area of tubes (weight) ..	1	0.54	0.47	0.30	0.23	
Heater						
Coefficient of heat transmission ..	1	1.6	1.7	2.0	4.0	on one side
Number of tubes	1	0.78	0.75	0.68	0.30	(ratio)
Length of tubes	1	0.82	0.79	0.74	0.85	
Surface area of tubes (weight) ..	1	0.64	0.59	0.50	0.25	

Every future increase that can be made in the temperature will for each 10 degrees F. lead to a saving in fuel of 0.75 per cent, i.e., for 40 degrees F. increase in temperature an improvement in the overall thermal efficiency of about 1 per cent may be expected.

When making a comparison with open-cycle gas turbines the pipes passing through the deck which are necessary for inhaling the combustion air and for discharging the combustion gases should also be borne in mind. Whereas a closed-cycle turbine requires practically the same quantity of fresh air and discharges about the same volumes of waste gas through the funnels as in the case of Diesel engines or steam plant, these volumes are many times greater for an open-cycle combustion gas turbine because of the large surplus air volume of its working process for the purpose of reducing the temperature.

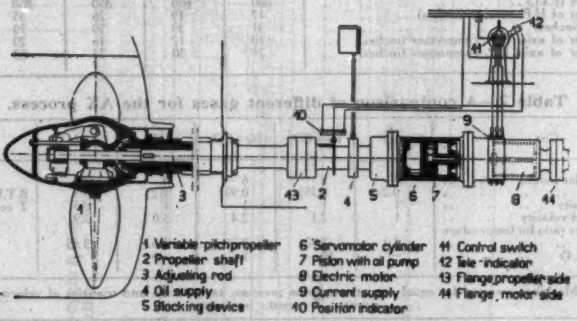

FIGURE 17.—THE ESCHER WYSS V.P. PROPELLER.

One cannot discuss new gas-turbine development for marine propulsion without mentioning the future development of the propelling means.

The most suitable solution for reverse operation which gives at the same time ideal operating conditions for the whole plant is the adoption of variable-pitch propellers, thus obviating the necessity of installing a separate turbine for propelling the vessel astern. From wide experience in the building of Kaplan-type water turbines we developed in 1934 such a new marine propeller, based on the same principles. No failures or defects have been reported concerning the 35 marine propellers already delivered. Figure 17 shows a cross-section of the Escher-Wyss V.P.-propeller.

BOOK REVIEW.

AIRCRAFT ELECTRICITY FOR THE MECHANIC, By Charles Edward Chapel. Published by Coward-McCann, New York:

A recent release which combines the theoretical and practical aspects of electricity as applied especially to aircraft.

The author, Director of Research and Development at Northrop Aeronautical Institute has published several books on diverse subjects.

THE RADIO AMATEUR'S HANDBOOK, Published by the American Radio League, West Hartford, Conn.

This standard handbook of 468 pages is the twenty-third edition, and contains chapters on principles, design, equipment and general subjects relating to radio.

ASSOCIATION NOTES.

Addresses.

Correct addresses are becoming more and more important. It is urged that members keep the Society informed. This is the only way you can be certain of receiving your Journal and other mail.

Society Lapel Button.

Shown below is an illustration of the lapel button of the Society. It is believed that it will be conceded that this is a very fine, dignified insignia. It is one-half inch in diameter. The oak leaves and lettering are red on a gold back-ground. It is available to all members at fifty cents (50c) each.

Membership Additions.

The following have joined the Society since the publication of the May, 1946, Journal. Addresses of personnel on ships not given.

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